7 of 12

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COAL MINING RESEARCH CENTRE

MULTIPLE BLOCK PLANE SHEAR SLOPE FAILURE

PART I: THEORETICAL ANALYSIS

by

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TABLE OF CONTENTS

	PAGE NO.
1. Introduction	1
2. Objectives and Approach	5
3. Nomenclature and Assumptions	6
4. Limiting Conditions for the Analysis	9
4.1 Conditions for the two slope case	9
4.2 Conditions defining the position of the n th and (n + 1) th cracks	9
4.3 Conditions defining the water table position	16
4.4 Number of possible solutions	16
5. General Equilibrium Equation	16
6. Computer Program Logic	22
7. References	22
APPENDIX 1: Detailed Case Calculations	A1

LIST OF FIGURES

FIGURE 1 Multiple Block Plane Shear Slope Failure
FIGURE 2 Early Movement of Lower Slope on the Clay Band (1)
FIGURE 3 Tension Cracks Defining failed Blocks in the Upper Crest
FIGURE 4 Tension Cracks Defining failed Blocks in the Intervening Bench
FIGURE 5 Block failure of the Lower Slope
FIGURE 6 Nomenclature
FIGURE 7 General Condition for a two slope case
FIGURE 8 Possible positions for the nth and (n+1)th cracks
FIGURE 9 Variation of (n+1)th crack position - Sub Cases A1 to A4
FIGURE 10 Variation of (n+1)th crack position - Sub Cases B1 to B3
FIGURE 11 Variation of (n+1)th crack position - Sub Cases C1, C2 & D1
FIGURE 12 Forces Acting on the Wedge
FIGURE 13 Program Subroutines
FIGURE 14 Case A.1.a
FIGURE 15 Case A.1.b
FIGURE 16 Case A.1.c
FIGURE 17 Case A.1.d
FIGURE 18 Case A.2.a
FIGURE 19 Case A.2.b
FIGURE 20 Case A.2.c
FIGURE 21 Case A.2.d
FIGURE 22 Case A.3.a
FIGURE 23 Case A.3.b
FIGURE 24 Case A.3.c
FIGURE 25 Case A.4.a
FIGURE 26 Case A.4.b
FIGURE 27 Case A.4.c
FIGURE 28 Case B.1.a
FIGURE 29 Case B.1.b
FIGURE 30 Case B.1.c
FIGURE 31 Case B.2.a
FIGURE 32 Case B.2.b
FIGURE 33 Case B.2.c
FIGURE 34 Case B.3.a
FIGURE 35 Case B.3.b
FIGURE 36 Case C.1.a
FIGURE 37 Case C.1.b
FIGURE 38 Case C.1.c
FIGURE 39 Case C.2.a
FIGURE 40 Case C.2.b
FIGURE 41 Case C.2.c
FIGURE 42 Case D.1.a
FIGURE 43 Case D.1.b

TABLES

TABLE 1 Case Codes
TABLE 2 **(Does not exist)**
TABLE 3 Summary of Formulae Case A
TABLE 4 Summary of Formulae - Cases B, C and D

1. Introduction

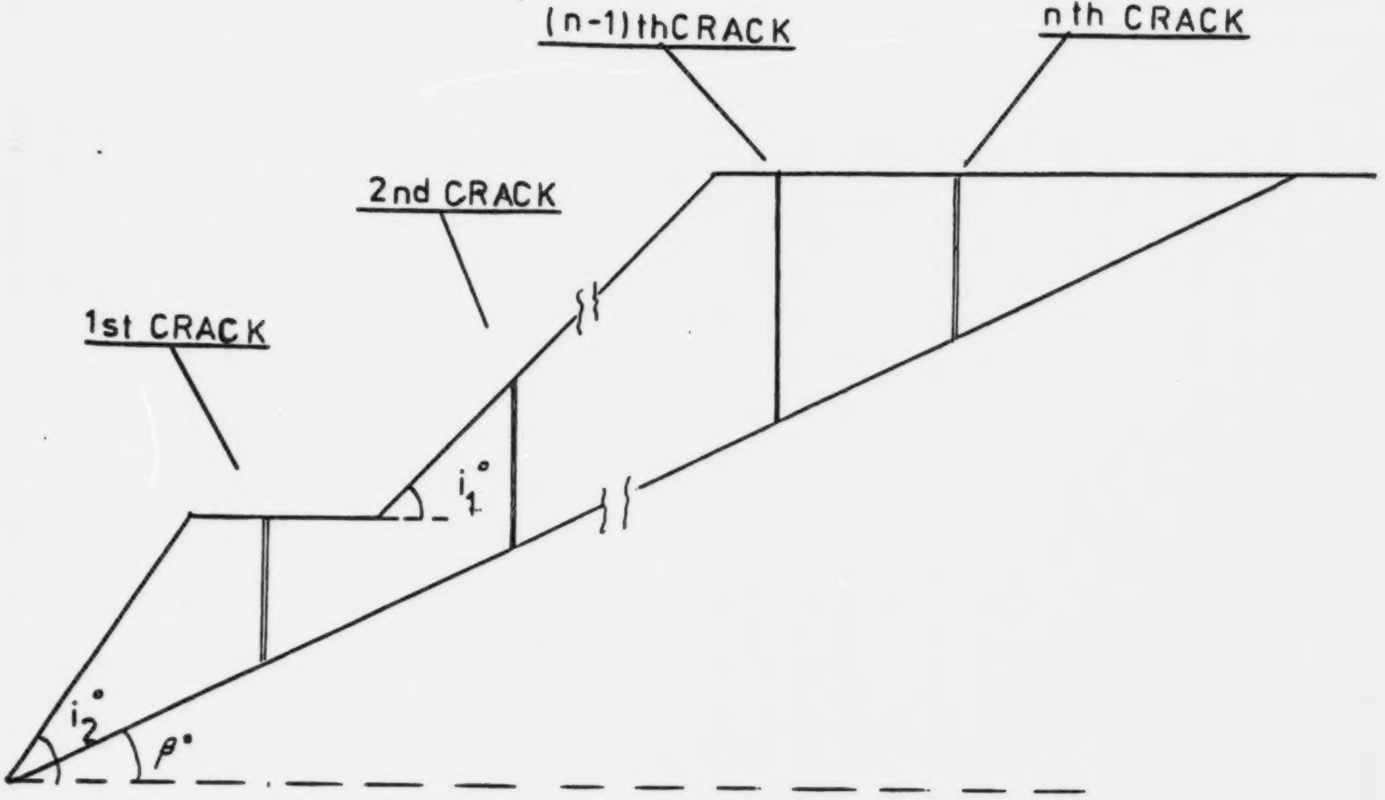
A number of high wall slope failures, which may be described as "multiple block plane shear failures", are occurring in some coal strip mines in the Alberta plains. These failures cause a rapid deterioration of the bench from which the dragline operates, reducing productivity and necessitating considerable bench maintenance to provide a safe stable bench prior to the next pass of the dragline.

These multiple block shear failures are invariably associated with the presence of low angle (± 5° to horizontal) bentonitic clay bands in the overburden, often immediately above the coal seam. Failure first occurs when a tension crack is formed in the slope face, the bench or the crest, which descends from the surface to the clay band. The block so detached then slides on the clay band. The detachment and subsequent movement of this first block removes confinement from the newly created slope face thus allowing a second tension crack to form further back in the slope or crest, this second block in turn slides on the clay band. In this manner a whole series of blocks may detach and slide as is evidenced by a series of tension cracks spaced back into the crest. This is illustrated in Figure 1 and the photographs in Figures 2 to 5 show the evidence of this type of failure occuring in Alberta strip mines.

The basic principles of plane shear failure in a simple slope are well documented in Volume 5.1 of the CANMET Pit Slope Manual. (1) However this volume does not address the somewhat more complex case of multiple block failure, neither does it address the analysis of the more complex geometry of two slopes with an intervening bench.

Part I of this report therefore develops the theory for multiple block shear failure for the case of two slopes with an intervening bench, and gives the computer program logic developed for the solution of the problem.

Part II gives the computer program. Part III of this report documents some case histories and compares these with the theoretical solution. Based on these results, the complications of mining to greater depths and ways of preventing and controlling such failures are discussed.


(n-1)thCRACK
nth CRACK
2nd CRACK
1st CRACK
i_1°
i_2°
β°

MULTIPLE BLOCK PLANE SHEAR
SLOPE FAILURE

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SCALE : -	DWG. No. : FIG:1

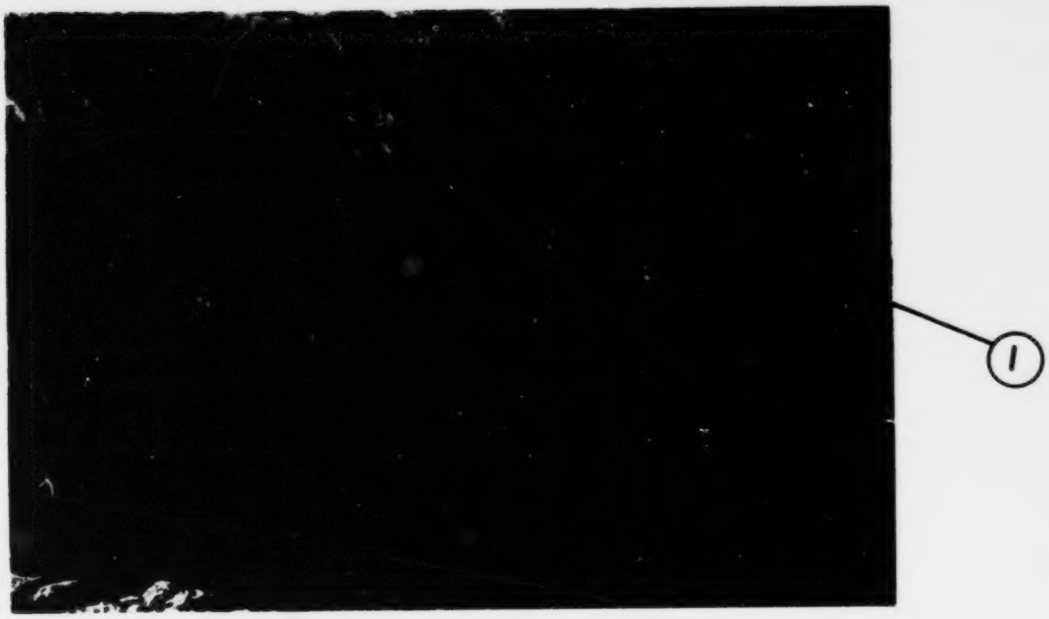


FIGURE 2: EARLY MOVEMENT OF LOWER SLOPE ON THE CLAY BAND (1)

FIGURE 3: TENSION CRACKS DEFINING FAILED BLOCKS IN THE UPPER CREST

FIGURE 4: TENSION CRACKS DEFINING FAILED BLOCKS IN THE INTERVENING BENCH

FIGURE 5: BLOCK FAILURE OF THE LOWER SLOPE

2. Objectives and Approach

The study objectives and approach were as follows:-

1. To develop the theoretical analysis of multiple block plane shear failure for pit walls comprising two slopes with an intervening bench, with a horizontal water table.

2. To write a computer program to perform this pit slope stability analysis:-
    a) to predict the position of the tension cracks (given the cohesion and angle of friction of the failure plane) or
    b) to determine the failed surface properties by back analysis given the tension crack positions, and ground water conditions
    c) to couple this program with the "Monte Carlo" sub routine given in the CANMET Pit Slope Manual enabling the distribution curves of the input parameters to be used to determine the probability of failure in this mode.

(The programming language will be Fortran IV).

3. To document the case histories of this mode of slope failure in two Alberta coal strip mines and to compare the theory with the case histories by:-
    a) visiting two mine sites where such failures are occurring, recording the slope angles, geometry and tension crack positions, etc.
    b) sampling the clay band and adjacent clay/rock surfaces and, from laboratory testing, determining the appropriate cohesion and friction angles.
    c) comparing the slope failures predicted by theory, using these laboratory sample results, with the field case histories.

4. To examine the influence of increasing overburden depth on this mode of failure and to discuss ways and means of preventing and controlling such failures.

5. To prepare the whole study as a report suitable for publication.

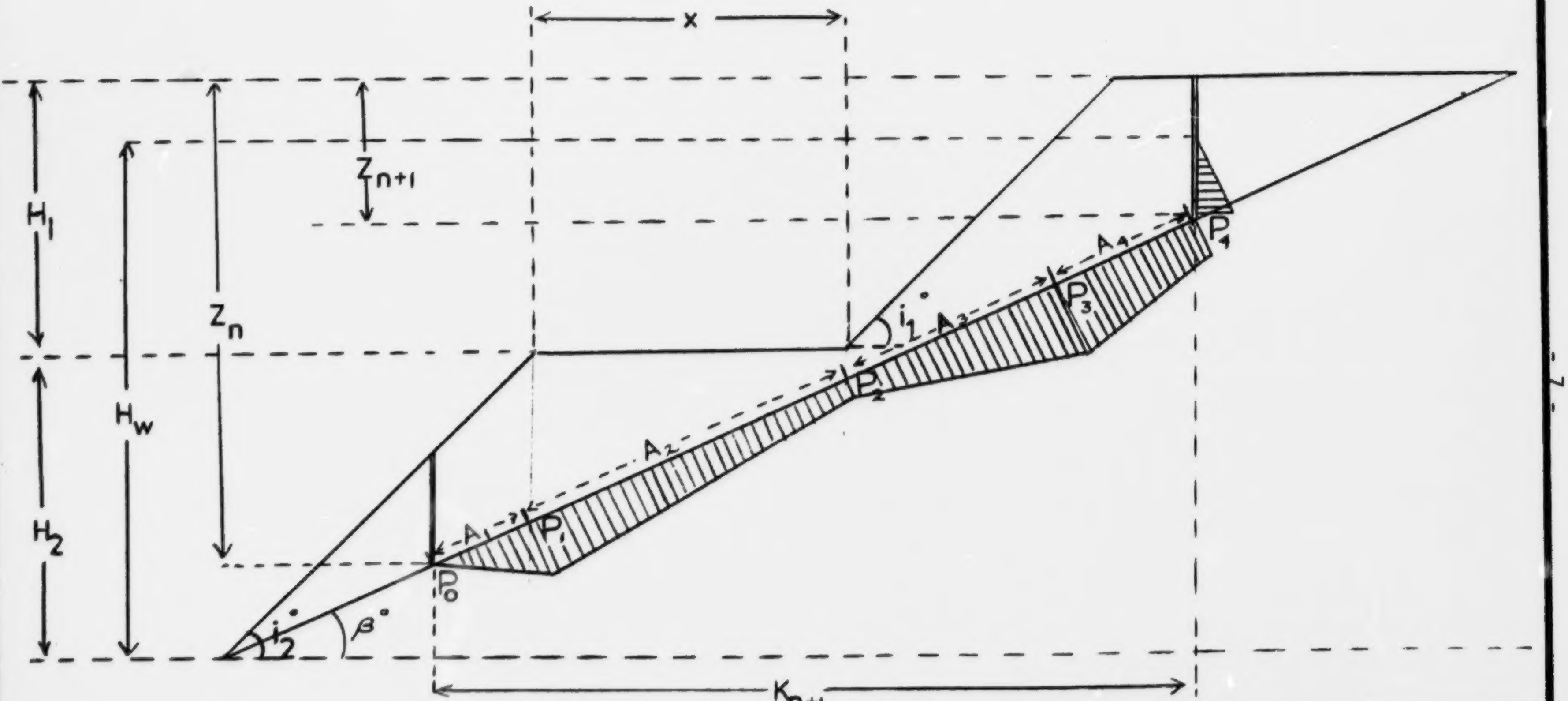
6. To develop a suitable technology transfer package including a de-briefing seminar.

3. Nomenclature and Assumption

The general case considered is illustrated in Figure 6; the highwall comprises two slopes at different angles separated by a bench. The stability of the wedge or block lying between the n th and (n+1) th crack is considered. The water table is assumed to be perched on the impervious failure plane and is assumed to be horizontal. In practice there is likely to be some drawdown of the water table near the slope face. Consequently this analysis is an "extreme case" and will be less stable than the drawdown case.

The geometrical parameters are also shown on Figure 6 and the nomenclature and dimensions used in the anlysis are listed below:-

		Imperical Units	S.I. Units
H_1	- height of the upper slope	ft.	m
H_2	- height of the lower slope	ft.	m
H_w	- height of the water table	ft.	m
i_1	- angle of the upper slope with the horizontal	degrees	
i_2	- angle of the lower slope with the horizontal	degrees	
x	- bench width	ft.	m
β	- angle of the failure plane with the horizontal	ft.	m
Z_n	- depth of the n th crack below surface	ft.	m
Z_{n+1}	- depth of the (n+1) th crack below surface	ft.	m
K_n	- horizontal distance between the (n-1) th and n th cracks = $(Z_{n-1} - Z_n) \cot \beta$	ft.	m
K_{n+1}	- horizontal distance between the n th and (n+1) th cracks	ft.	m
A	- $H_1 + H_2 - Z_n$	ft.	m
B	- $H_1 + H_2 - Z_{n+1}$	ft.	m
α	- $Z_{n+1} + H_w - H_1 - H_2$	ft.	m
W	- Weight of failed wedge between n th and (n+1) th cracks	lbs.	kg.
γ	- Density of the rock in the failed wedge	lbs/cu.ft.	kg/m^3
γ_w	- Density of the rock in the failed wedge	lbs/cu.ft.	kg/m^3
P_o	- Water pressure at the bottom of the n th crack	lbs/sq.ft.	kPa
P_1	- Maximum water pressure acting on the failed plane under the lower slope	lbs/sq.ft.	kPa
P_2	- water pressure acting on the failed plane under the toe of the upper slope/or as indicated on the appropriate case figure.	lbs/sq.ft.	kPa
P_3	- maximum water pressure acting on the failed plane under the upper slope	lbs/sq.ft.	kPa
P_4	- Water pressure at the bottom of the (n+1) th crack, or the minimum water pressure (=0) at the intersection of the water table with the failure plane under the upper slope.	lbs/sq.ft.	kPa


x
H_1
H_w
H_2
Z_n
Z_{n+1}
i_1°
i_2°
β°
P_0
P_1
P_2
P_3
P_4
A_1
A_2
A_3
A_4
K_{n+1}

NOMENCLATURE

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			Imperical Units	S.I. Units
A_T	-	Total area of the failure plane, of unit depth, between the n th and (n+1) th cracks.	sq. ft.	m^2
A_1	-	Area of the failure plane between pressure points P_o and P_1	sq. ft.	m^2
A_2	-	Area of the failure plane between pressure points P_1 and P_2	sq. ft.	m^2
A_3	-	Area of the failure plane between pressure points P_2 and P_3	sq. ft.	m^2
A_4	-	Area of the failure plane between pressure points P_3 and P_4	sq. ft.	m^2
U	-	Total uplift force due to water pressure acting as the failure plane between the n th and (n+1) th cracks	lbs.	N
V	-	Force applied to the failed wedge by water in the (n+1) th crack	lbs.	N
Y	-	Resisting force due to tensile strength across the potential (n+1) th crack	lbs.	N
T	-	Tensile strength of the rock	lbs/sq.ft.	kPa
R_T	-	Total force resisting failure	lbs.	N
	=	$cA_T + \tan \phi \left\{ W \cos \beta - U - V \sin\beta + Y \sin \beta \right\}$		
c	=	Effective cohesion on the failure plane	lbs/sq.ft.	kPa
Q	=	Effective angle of friction on the failure plane	degrees	
X	=	$(\cot i_1 - \cot i_2)$	-	
S	=	$(\cot i_1 + \cot i_2)$	-	
R	=	$A\,(1 + \cot \beta \tan i_1) - x \tan_{\beta} - H_2 \cot i_2 \tan \beta$	ft	m
Δ	=	Incremental horizontal distance, $K_{n+1} = a\Delta$ where a = integer		
n	=	crack number		
s	=	solution number (1 or 2)		

4. Limiting Conditions for the analysis

4.1 Condition for a Two Slope Case

It is seen from Figure 7 that the condition

$$H_2 \cot \beta > H_2 \cot i_2 + x$$

represents the "general two slope" condition. If $H_2 \cot \beta$ is $\nless H_2 \cot i_2 + x$ the failure plane intersects the bench and the case breaks down into two separate single slope cases, each of which can be analysed separately.

4.2 Conditions Defining the positions of the n th and (n+1) th cracks

There can be four potential positions of the n th crack, as illustrated in Figure 8:

Case A: The n th crack will be in the lower slope if:

$0 < K_1 + K_2 \ldots + K_n < H_2 \cot i_2$

Case B: The n th crack will be in the bench if:

$H_2 \cot i_2 < K_1 + K_2 \ldots \; Kn < H_2 \cot i_2 + x$

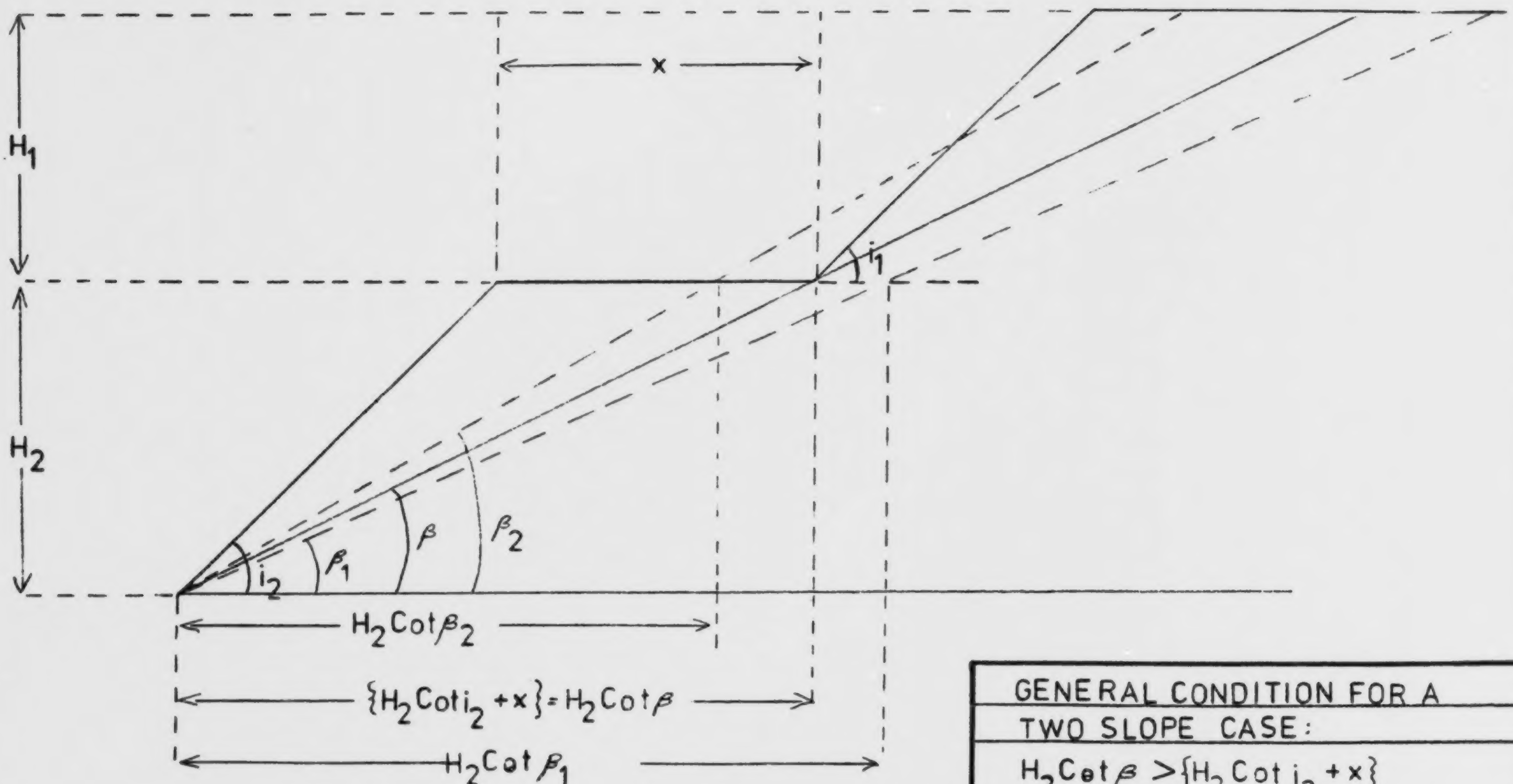
Case C: The n th crack will be in the upper slope if:

$H_2 \cot i_2 + x < K_1 + K_2 + \; Kn < H_2 \cot i_2 + x + H_1 \cot i$

Case D: The n th crack will be in the crest if:

$H_2 \cot i_2 + x + H_1 \cot i_1 < K_1 + K_2 \ldots + \; Kn < (H_1 + H_2) \cot \beta$

Further, with each of the above cases for the n th crack positions there are several possible positions for the (n+1) th crack. These sub cases are illustrated in Figures 9, 10 and 11, and the condition for the (n+1) th crack positions are given by


x
H$_1$
H$_2$
i_1
i_2
β_1
β
β_2
$H_2 Cot \beta_2$
$\{H_2 Cot i_2 + x\} = H_2 Cot \beta$
$H_2 Cot \beta_1$

GENERAL CONDITION FOR A TWO SLOPE CASE:

$H_2 Cot \beta > \{H_2 Cot i_2 + x\}$

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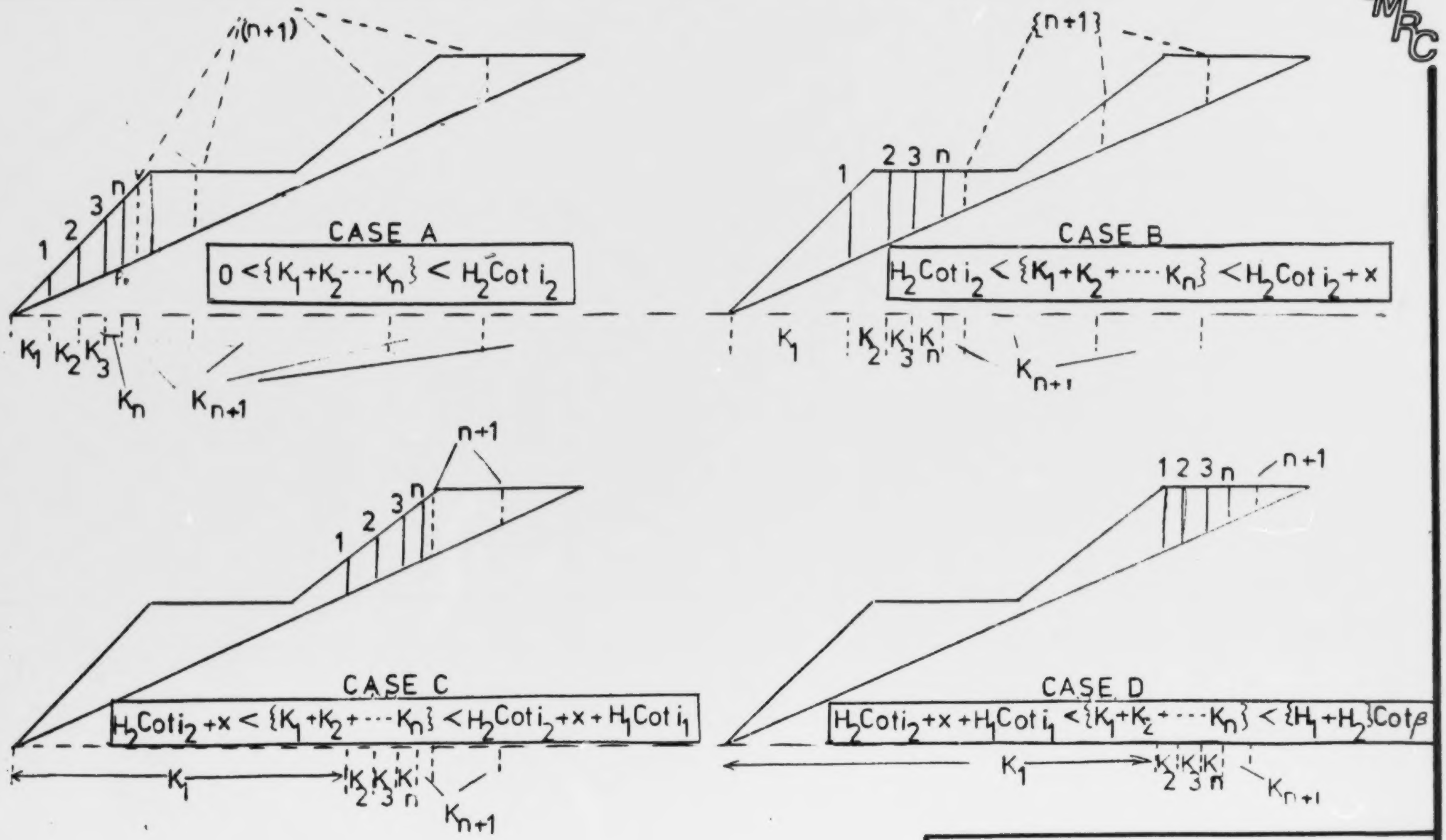
(n+1)
1
2
3
n
CASE A
$0 < \{K_1 + K_2 \cdots K_n\} < H_2 \operatorname{Cot} i_2$
K_1 K_2 K_3
K_n
K_{n+1}
{n+1}
1
2 3 n
CASE B
$H_2 \operatorname{Cot} i_2 < \{K_1 + K_2 + \cdots K_n\} < H_2 \operatorname{Cot} i_2 + x$
K_1
K_2 K_3 K_n
K_{n+1}
n+1
1
2
3
n
CASE C
$H_2 \operatorname{Cot} i_2 + x < \{K_1 + K_2 + \cdots K_n\} < H_2 \operatorname{Cot} i_2 + x + H_1 \operatorname{Cot} i_1$
K_1
K_2 K_3 K_n
K_{n+1}
1 2 3 n
n+1
CASE D
$H_2 \operatorname{Cot} i_2 + x + H_1 \operatorname{Cot} i_1 < \{K_1 + K_2 + \cdots K_n\} < \{H_1 + H_2\} \operatorname{Cot} \beta$
K_1
K_2 K_3 K_n
K_{n+1}

POSSIBLE POSITIONS FOR
THE nth AND (n+1)th CRACKS

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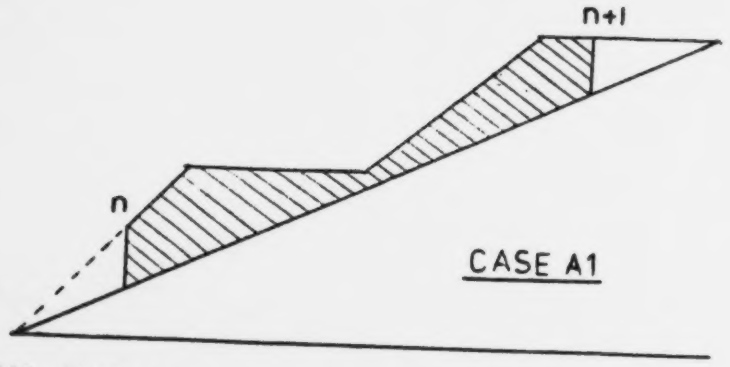
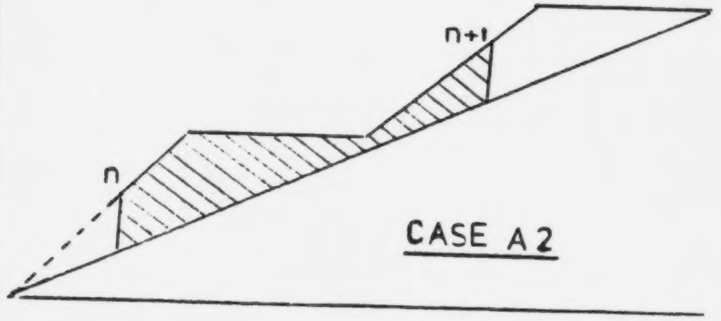
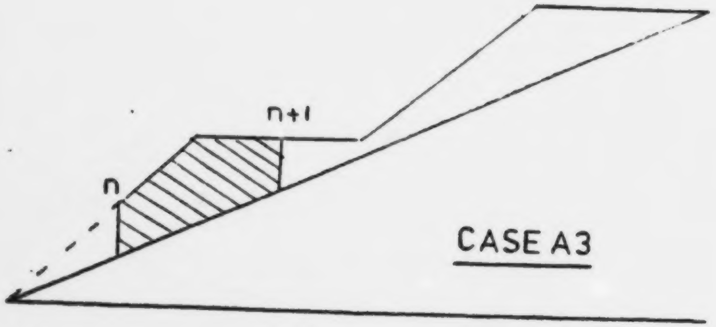


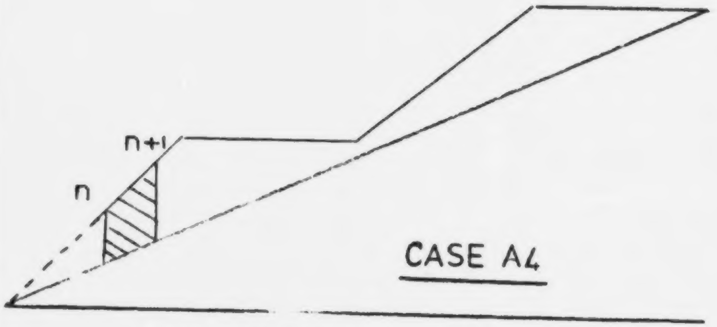
$(H_1+H_2)\cot\beta - A\cot\beta > K_{n+1} > H_2\cot i_2 + x + H_1\cot i_1 - A\cot\beta$



$H_2\cot i_2 + x + H_1\cot i_1 - A\cot\beta > K_{n+1} > H_2\cot i_2 + x - A\cot\beta$.



$H_2\cot i_2 + x - A\cot\beta > K_{n+1} > H_2\cot i_2 - A\cot\beta$



$H_2\cot i_2 - A\cot\beta > K_{n+1} > 0$

VARIATION OF (n +1) th CRACK
POSITION - SUB CASES A1 to A4

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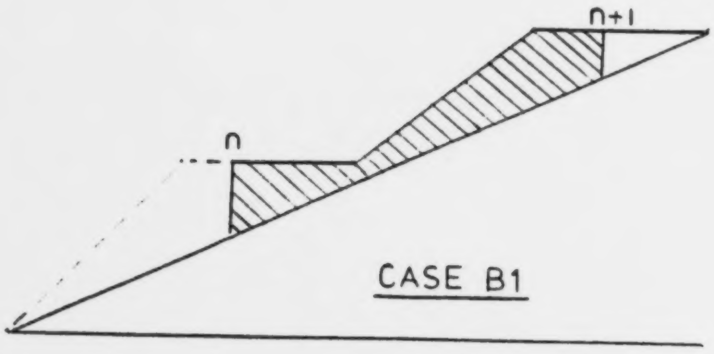
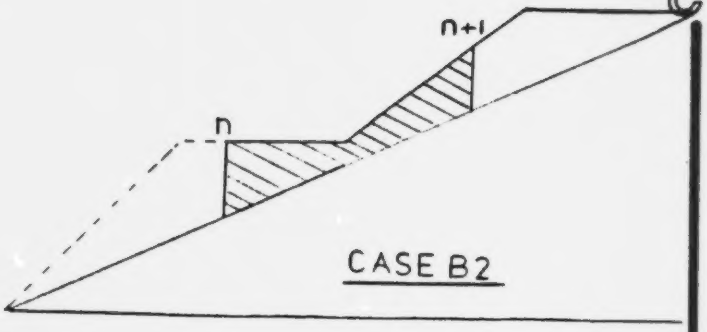


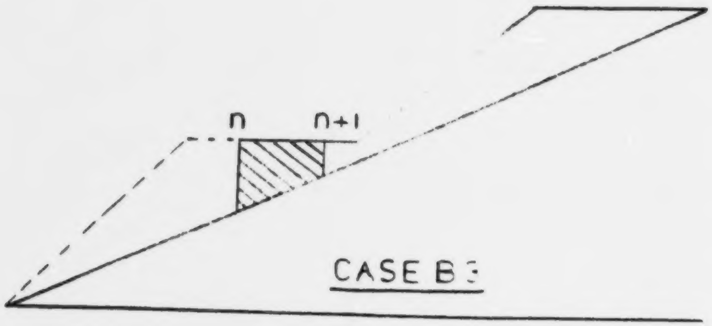
CASE B1

$(H_1+H_2)\cot\beta - A\cot\beta > K_{n+1} > H_2\cot i_2 + x + H_1\cot i_1 - A\cot\beta$



CASE B2

$H_2\cot i_2 + x + H_1\cot i_1 - A\cot\beta > K_{n+1} > H_2\cot i_2 + x - A\cot\beta$



CASE B3

$H_2\cot i_2 + x - A\cot\beta > K_{n+1} > 0$

VARIATION OF (n+1) th CRACK POSITION - SUB CASES B1 to B3	
DWN. BY : KE	DATE :
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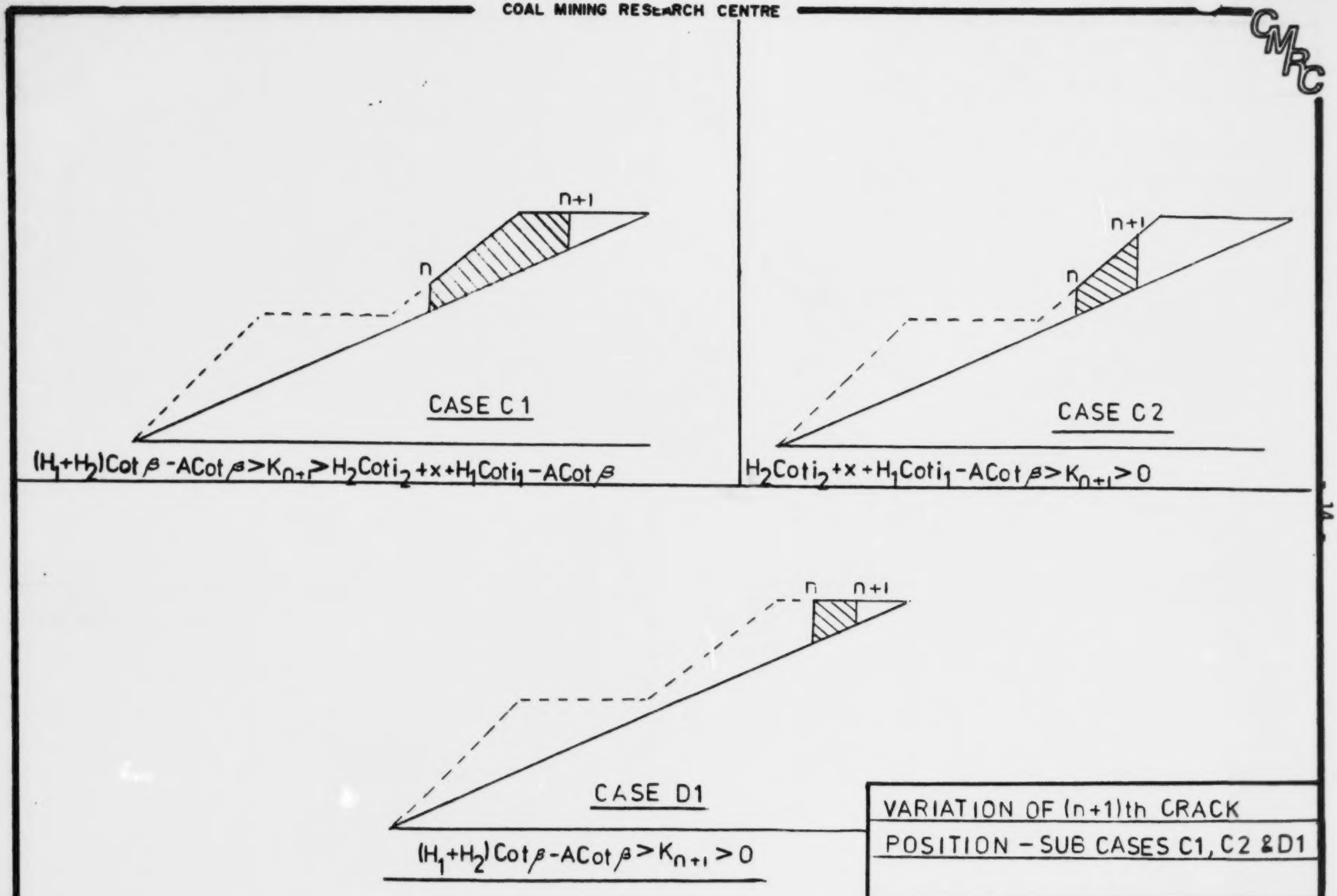
n
n+1
CASE C1
n
n+1
CASE C2
n
n+1
CASE D1

$(H_1+H_2)\cot\beta - A\cot\beta > K_{n+1} > H_2\cot i_2 + x + H_1\cot i_1 - A\cot\beta$

$H_2\cot i_2 + x + H_1\cot i_1 - A\cot\beta > K_{n+1} > 0$

$(H_1+H_2)\cot\beta - A\cot\beta > K_{n+1} > 0$

VARIATION OF (n+1)th CRACK POSITION - SUB CASES C1, C2 & D1

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Case A1 - (n+1) th crack in the crest

$(H_1 + H_2) \cot \beta - A \cot \beta > K_{n+1} > H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$

Case A2 - (n+1) th crack in the upper slope

$H_2 \cot i_2 + x + H_1 \cot i_1, - A \cot \beta > K_{n+1} > H_2 \cot i_2 + x - A \cot \beta$

Case A3 - (n+1) th crack in the bench

$H_2 \cot i_2 + x - A \cot \beta > K_{n+1} > H_2 \cot i_2 - A \cot \beta$

Case A4 - (n+1) th crack in the lower slope

$H_2 \cot i_2 - A \cot \beta > K_{n+1} > 0$

Case B1 - (n+1) crack in the crest

$(H_1 + H_2) \text{Cot } \beta - A \cot \beta > K_{n+1} > H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$

Case B2 - (n+1) th crack in upper slope

$H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta > K_{n+1} > H_2 \cot i_2 + x - A \cot \beta$

Case B3 - (n+1) th crack in the bench

$H_2 \cot i_2 + x - A \cot \beta > K_{n+1} > 0$

Case C1 - (n+1) th crack in the crest

$(H_1 + H_2) \cot \beta - A \cot \beta > K_{n+1} > H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$

Case C2 - (n+1) th crack in the upper slope

$H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta > K_{n+1} > 0$

Case D1 - (n+1) th crack in the crest

$(H_1 + H_2) \cot \beta - A \cot \beta > K_{n+1} > 0$

The above sets of conditions define the positions of the n th and (n+1) th cracks and thus define the wedge whose stability is to be analysed.

4.3 Conditions defining the water table position

For all of the above cases, the forces acting on the wedge, will depend on the level of the water table relative to the crack positions. Basically there are four possible water table positions:-

(a) above the bottom of the (n+1) th crack
(b) below the bottom of the (n+1) th crack but above H_2
(c) below H_2 but above the top of the n th crack
and (d) below the top of the n th crack.

However, all of these positions will not be applicable to all of the above cases. Table 1 summarises the crack positions and the applicable water table positions. This table also defines the coding used to describe each possible case. There are in total 30 cases which require analysis.

The conditions for the water table positions are developed, for each case, in Appendix 1.

4.4 Number of possible solutions

With this general geometry it is theoretically possible that there may be two equally valid solutions for a safety factor of unity for a particular case because all equations for the weight of the wedge, W, explicitly or implicitly contain Z_{n+1}^2 as a term. However, one solution may be physically meaningless (i.e. - ve); however the program should be written so as to consider the possibilities of two solutions for each potential crack position.

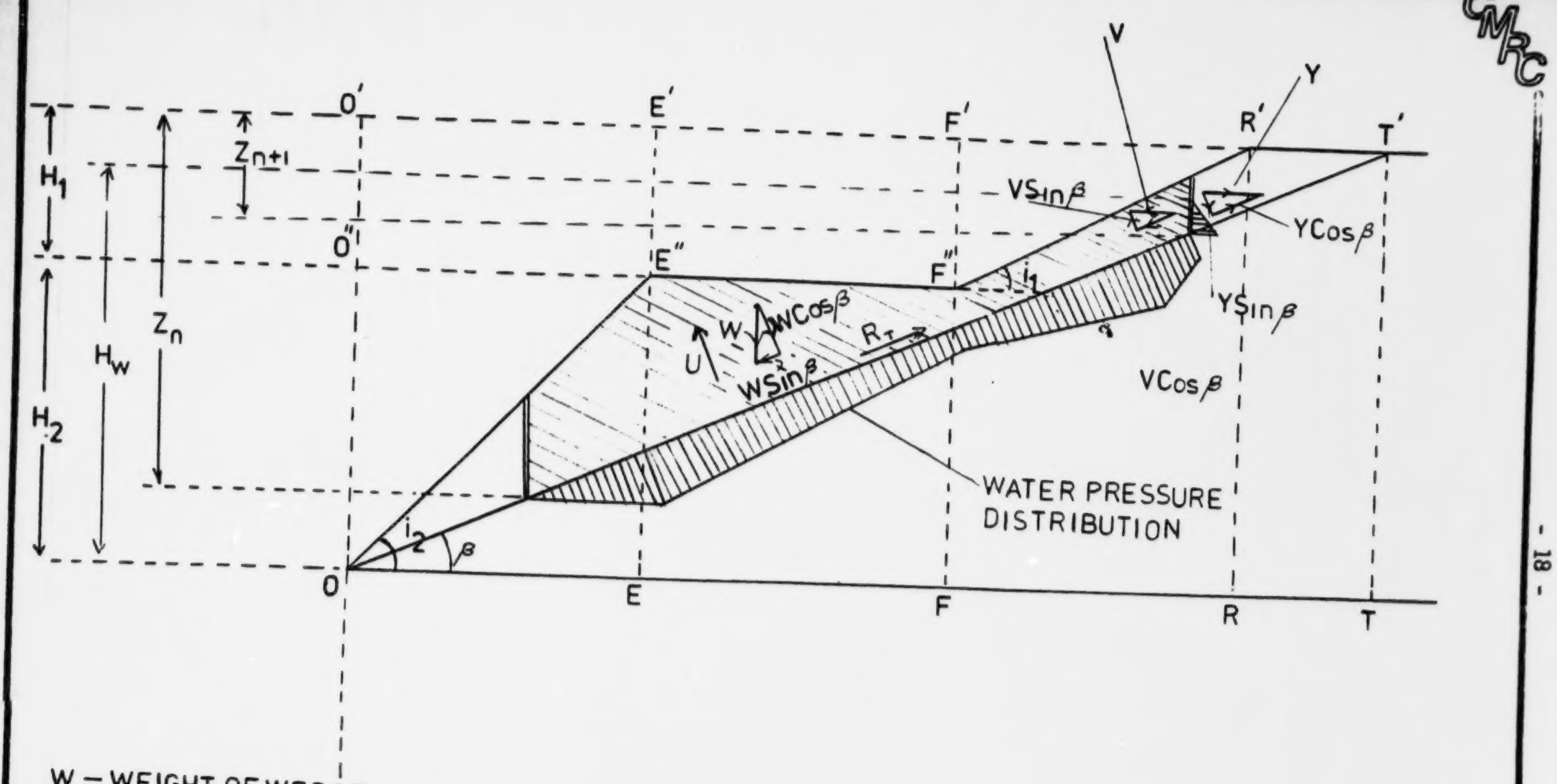
5. General Equilibrium Equation

The forces, defined in the nomenclature, and acting on the failing block are illustrated for one case in Figure 12.

For stability:-
The total resisting force > the total disturbing force.

TABLE 1: CASE CODES

Position of n th crack	Position of (n+1) crack	Position of Water Table	Case Code
A. In Lower Slope	1. In Crest	(a) Above (n+1) crack bottom	A.1.a.
		(b) Below (n+1) crack bottom/above H_2	A.1.b.
		(c) Below H_2/Above n th crack top	A.1.c.
		(d) Below n th crack top	A.1.d.
	2. In Upper Slope	(a) Above (n+1) crack bottom	A.2.a.
		(b) Below (n+1) crack bottom/above H_2	A.2.b.
		(c) Below H_2/above n th crack top	A.2.c.
		(d) Below n th crack top	A.2.d.
	3. In Bench	(a) Above (n+1) crack bottom	A.3.a.
		(b) Below (n+1) crack bottom/above n th crack top	A.3.b.
		(c) Below n th crack top	A.3.c.
	4. In Lower Slope	(a) Above (n+1) crack bottom	A.4.a.
		(b) Below (n+1) crack bottom/above n th crack top	A.4.b.
		(c) Below n th crack top	A.4.c.
B. In Bench	1. In Crest	(a) Above (n+1) crack bottom	B.1.a.
		(b) Below (n+1) crack bottom/above H_2	B.1.b.
		(c) Below H_2 (i.e. Below n th crack top)	B.1.c.
	2. In Upper Slope	(a) Above (n+1) crack bottom	B.2.a.
		(b) Below (n+1) crack bottom/above H_2)	B.2.b.
		(c) Below H_2 (i.e. Below n th crack top)	B.2.c.
	3. In Bench	(a) Above (n+1) crack bottom	B.3.a.
		(b) Below (n+1) crack bottom	B.3.b.
C. In Upper Slope	1. In Crest	(a) Above (n+1) crack bottom	C.1.a.
		(b) Below (n+1) crack bottom/above n th crack top	C.1.b.
		(c) Below n th crack top	C.1.c.
	2. In Upper Slope	(a) Above (n+1) crack bottom	C.2.a.
		(b) Below (n+1) crack bottom/above n th crack top	C.2.b.
		(c) Below n th crack top	C.2.c.
D. In Crest	1. In Crest	(a) Above (n+1) crack bottom	D.1.a.
		(b) Below (n+1) crack bottom	D.1.b.


CMRC
O'
E'
F'
R'
T'
V
Y
H_1
H_2
H_w
Z_n
Z_{n+1}
O''
E''
F''
VSinβ
YCosβ
YSinβ
VCosβ
i_1
i_2
β
W
U
WCosβ
WSinβ
R_T
WATER PRESSURE DISTRIBUTION
O
E
F
R
T

W – WEIGHT OF WEDGE

U – UPLIFT FORCE

V – FORCE DUE TO WATER IN (n+1)th CRACK

Y – FORCE DUE TO TENSILE STRENGTH

R_T – TOTAL FORCE RESISTING FAILURE

$= cA_T + \tan\phi \{ W\cos\beta - U - (V-Y)\sin\beta$

WHERE c IS THE COHESION & φ THE FRICTION ANGLE

FORCES ACTING ON THE WEDGE	
DWN. BY : K.B.	DATE :
SCALE : –	DWG. No. : FIG:12

Resolving the forces parallel to the plane of failure gives:-

$$cA_T \tan \phi \; W \cos \beta - U - (V-Y) \sin \beta > W \sin \beta + (V-Y) \cos \beta \qquad (1)$$

and, defining the safety factor, S.F. as =

$$\frac{\text{Total resisting force}}{\text{Total disturbing force}} = \frac{cA_T + \tan \phi \; W \cos \beta - U - (V-Y) \sin \beta}{W \sin \beta + (V-Y) \cos \beta}$$

A crack will form when safety factor equals unity.

Thus, at the moment of failure, putting the safety factor equal to 1 in equation (2), then the position (horizontal distance) K_{n+1} of the (n+1) th crack can be calculated by solving this equation for K_{n+1}.

This equilibrium equation will apply for all the cases considered; however the values of the forces W, U, V, Y, c and A_T will vary for each case. These forces have been derived in Appendix 1 for each of the 30 possible cases.

Tables 3 and 4 summarise the equations derived in Appendix 1 for calculating these forces and gives also a summary of the conditions defining the n th, (n+1) th crack positions and water table positions for each of these cases.

A computer program has been written to perform these calculations and solve for the crack positions.

TABLE 3 : SUMMARY OF FORMULAE CASE A

CASE #	A1(a)	A1(b)	A1(c)	A1(d)	A2(a)	A2(b)	A2(c)	A2(b)
n th crack position	IN THE LOWER SLOPE				IN THE LOWER SLOPE			
n th crack condition	$0 < \{K_1+K_2+\ldots\ldots K_n\} < H_2\cot i_2$				$0 < \{K_1+K_2+\ldots\ldots K_n\} < H_2\cot i_2$			
(n+1) th position	IN THE CREST				IN THE UPPER SLOPE			
(n+1)th condition	$(H_1+H_2)\cot\beta - A\cot\beta > K_{n+1} > H_2\cot i_2 + x + H_1\cot i_1 - A\cot\beta$				$H_2\cot i_2 + x - A\cot\beta < K_{n+1} < H_2\cot i_2 + x + H_1\cot i_1 - A\cot\beta$			
Weight Wedge W	$\frac{\gamma}{2}\{\cot\beta[(H_1+H_2)^2 - Z_{n+1}^2] + A^2\cot\beta[1-\cot\beta\tan i_2] - \cot i_2[H_1+H_2]^2 - H_1^2[\cot i_1-\cot i_2] - 2H_1x\}$				$\frac{\gamma}{2}\{\cot\beta[(H_1+H_2)^2 - Z_{n+1}^2] + A^2\cot\beta[1-\cot\beta\tan i_2] - \cot i_2[H_1+H_2]^2 - H_1^2[\cot i_1-\cot i_2] - 2H_1x - \tan i_1[H_2\cot i_2 + x + H_1\cot i_1 - B\cot\beta]^2\}$			
* Water Table position	ABOVE (n+1) BOTTOM	BELOW (n+1)/ABOVE H_2	BELOW H_2/ABOVE n th TOP	BELOW n th TOP	ABOVE (n+1) BOTTOM	BELOW (n+1)/ABOVE H_2	BELOW H_2/ABOVE n th TOP	BELOW n th TOP
* Water Table condition	$Hw > B$	$B > Hw > H_2$	$H_2 > Hw > A\cot\beta\tan i_2$	$Hw < A\cot\beta\tan i_2$	$Hw > B$	$H_2 < Hw < B$	$A\cot\beta\tan i_2 < Hw < H_2$	$Hw < A\cot\beta\tan i_2$
P_0	0				0			
P_1	$\gamma_w H_2(1-\cot i_2\tan\beta)$			0	$\gamma_w H_2(1-\cot i_2\tan\beta)$			0
P_2	$\gamma_w\{H_2[1-\cot i_2\tan\beta] - x\tan\beta\}$		0		$\gamma_w\{H_2(1-\cot i_2\tan\beta) - x\tan\beta\}$		0	
P_3	$\gamma_w\{Hw+\tan\beta[H_2(\cot i_1-\cot i_2) - Hw\cot i_1 - x]\}$		0		$\gamma_w\{Hw+\tan\beta[H_2(\cot i_1-\cot i_2) - Hw\cot i_1 - x]\}$		0	
P_4	$\gamma_w\alpha$	0			$\gamma_w\alpha$	0		
A_T	$[1/\sin\beta]\{B-A\}$				$[1/\sin\beta]\{B-A\}$			
A_1	$[1/\sin\beta]\{H_2\cot i_2\tan\beta - A\}$			N.R.	$[1/\sin\beta]\{H_2\cot i_2\tan\beta - A\}$			N.R.
A_2	$[1/\sin\beta]\{x\tan\beta\}$		$[1/\sin\beta]\{Hw(1-\cot i_2\tan\beta)\}$	N.R.	$[1/\sin\beta]\{x\tan\beta\}$		$[1/\sin\beta]\{Hw(1-\cot i_2\tan\beta)\}$	N.R.
A_3	$[1/\sin\beta]\{(Hw-H_2)\cot i_1\tan\beta\}$		N.R.		$[1/\sin\beta]\{(Hw-H_2)\cot i_1\tan\beta\}$		N.R.	
A_4	$\frac{1}{\sin\beta}\{B+\tan\beta[H_2X-Hw\cot i_1-x]\}$	$\frac{1}{\sin\beta}\{B+\tan\beta[H_2X-Hw\cot i_1-x]-\alpha\}$	N.R.		$\frac{1}{\sin\beta}\{B+\tan\beta[H_2X-Hw\cot i_1-x]\}$	$\frac{1}{\sin\beta}\{\tan\beta[H_2(\cot i_1-\cot i_2)-Hw\cot i_1-x]+Hw\}$	N.R.	
U	$1/2\{[P_3+P_4]A_4+[P_2+P_3]A_3+[P_2+P_1]A_2+[P_1+P_0]A_1\}$			0	$1/2\{(P_3+P_4)A_4+(P_2+P_3)A_3+(P_2+P_1)A_2+(P_1+P_0)A_1\}$			
V	$\gamma_w/2\cdot\alpha^2$	0			$\gamma_w/2\cdot\alpha^2$	0		
Y	$T\cdot Z_{n+1}$				$T\{Z_{n+1}[1+\cot\beta\tan i_1] - H_1[1+\cot\beta\tan i_1] - H_2\tan i_1[\cot\beta+\cot i_2] - x\tan i_1\}$			

CASE #	A3(a)	A3(b)	A3(c)	A4(a)	A4(b)	A4(c)	
n th crack position	IN LOWER SLOPE			IN LOWER SLOPE			
n th crack condition	$0 < \{K_1+K_2+\ldots\ldots K_n\} < H_2\cot i_2$			$0 < \{K_1+K_2+\ldots\ldots K_n\} < H_2\cot i_2$			
(n+1) th position	IN THE BENCH			IN THE LOWER SLOPE			
(n+1)th condition	$H_2\cot i_2 - A\cot\beta < K_{n+1} < H_2\cot i_2 + x - A\cot\beta$			$0 < K_{n+1} < H_2\cot i_2 - A\cot\beta$			
Weight Wedge W	$\gamma/2\{H_2^2[\cot\beta-\cot i_2] + A^2\cot\beta(1-\cot\beta\tan i_2) - (H_2-B)^2\cot\beta\}$			$\gamma/2\ \cot\beta\{(\cot\beta\tan i_2 - 1)(B^2-A^2)\}$			
* Water Table position	ABOVE (n+1) BOTTOM	BELOW (n+1)/ABOVE n th TOP	BELOW n th TOP	ABOVE (n+1) BOTTOM	BELOW (n+1)/ABOVE n th TOP	BELOW n th TOP	
* Water Table condition	$Hw > B$	$A\cot\beta\tan i_2 < Hw < B$	$Hw < A\cot\beta\tan i_2$	$Hw > B$	$A\cot\beta\tan i_2 < Hw < B$	$Hw < A\cot\beta\tan i_2$	
P_0	0			0			
P_1	$\gamma_w Hw(1-\cot i_2\tan\beta)$		0	$\gamma_w H_w(1-\cot i_2\tan\beta)$		0	
P_2	$\gamma_w\alpha$	0		$\gamma_w\alpha$	0		
P_3	0			0			
P_4	0			0			
A_T	$1/\sin\beta\{B-A\}$			$[1/\sin\beta]\{B-A\}$			
A_1	$[1/\sin\beta]\{Hw\cot i_2\tan\beta - A\}$	$[1/\sin\beta]\{B\cot i_2\tan\beta - A\}$	N.R.	$[1/\sin\beta]\{Hw\cot i_2\tan\beta - A\}$		N.R.	
A_2	$[1/\sin\beta]\{B-Hw\cot i_2\tan\beta\}$	$[1/\sin\beta][Hw\{1-\cot i_2\tan\beta\}]$	N.R.	$[1/\sin\beta]\{B-Hw\cot i_2\tan\beta\}$	$[1/\sin\beta]\{Hw(1-\cot i_2\tan\beta)\}$	N.R.	
A_3	N.R.			N.R.			
A_4	N.R.			N.R.			
U	$1/2\{(P_1+P_2)A_1+(P_1+P_2)A_2\}$		0	$1/2\{(P_1+P_2)A_1+(P_1+P_2)A_2\}$		0	
V	$\gamma_w/2\cdot\alpha^2$	0		$\gamma_w/2\cdot\alpha^2$	0		
Y	$T(Z_{n+1}-H_1)$			$T\{Z_{n+1}-H_1-H_2+B\cot\beta\tan i_2\}$			

* Extra Statements RE Water Table

Cases A3 : When $Hw > H_2$ put $Hw = H_2$

Cases A2 : When $Hw > H_2(1-\cot i_2\tan i_1) + B\cot\beta\tan i_1 - x\tan i_1$ put Hw = this value

Cases A4 : When $Hw > B\cot\beta\tan i$ put Hw = this value

WHERE
N.R. = Not Required
$A = H_1+H_2-Z_n$
$B = H_1+H_2-Z_{n+1}$
$\alpha = Z_{n+1}+Hw-H_1-H_2$
$X = (\cot i_1-\cot i_2)$

CMRC

TABLE 4 : SUMMARY OF FORMULAE-CASES B,C AND D

CASE ⇒	B1 (a)	B1 (b)	B1 (c)	B2 (a)	B2 (b)	B2 (c)	B3 (a)	B3 (b)
n th crack position	IN THE BENCH			IN THE BENCH			IN THE BENCH	
n th crack condition	$H_2 \cot i_2 < \{K_1+K_2 \ldots K_n\} < H_2 \cot i_2 + x$			$H_2 \cot i_2 < \{K_1+K_2 \ldots K_n\} < H_2 \cot i_2 + x$			$H_2 \cot i_2 < \{K_1+K_2 \ldots K_n\} < H_2 \cot i_2 + x$	
(n+1)th position	IN THE CREST			IN THE UPPER SLOPE			IN THE BENCH	
(n+1)th condition	$(H_1+H_2)\cot\beta - A\cot\beta > K_{n+1} > H_2\cot i_2 + x + H_1\cot i_1 - A\cot\beta$			$H_2\cot i_2 + x - A\cot\beta < K_{n+1} < H_2\cot i_2 + x + H_1\cot i_1 - A\cot\beta$			$0 < K_{n+1} < H_2\cot i_2 + x - A\cot\beta$	
Weight Wedge W	$\frac{\gamma}{2}\{\cot\beta[Z_n^2 - Z_{n+1}^2] + H_1[2A\cot\beta - 2H_2\cot i_2 - H_1\cot i_1 - 2x]\}$			$\frac{\gamma}{2}\{\cot\beta[Z_n^2 - Z_{n+1}^2] + H_1[2A\cot\beta - 2H_2\cot i_2 - H_1\cot i_1 - 2x] + [H_2\cot i_2 + x + H_1\cot i_1 - B\cot\beta]^2\tan\beta\}$			$\frac{\gamma}{2} K_{n+1}\{2H_2 - (B+A)\}$	
* Water Table position	ABOVE (n+1)th BOTTOM	BELOW (n+1)/ABOVE H_2	BELOW H_2	ABOVE BOTTOM (n+1)	BELOW (n+1)/ABOVE H_2	BELOW H_2	ABOVE BOTTOM (n+1)	BELOW BOTTOM (n+1)
* Water Table condition	$H_w > B$	$H_2 < H_w < B$	$H_w < H_2$	$H_w > B$	$H_2 < H_w < B$	$H_w < H_2$	$H_w > B$	$H_w < B$
P_0	0			0			0	
P_1	N.R.			N.R.			N.R.	
P_2	$\gamma_w\{H_2(1-\cot i_2\tan\beta) - x\tan\beta\}$		0	$\gamma_w\{H_2(1-\cot i_2\tan\beta) - x\tan\beta\}$		0	$\gamma_w\alpha$	0
P_3	$\gamma_w\{H_w(1-\cot i_1\tan\beta) + \tan\beta[H_2X - x]\}$		0	$\gamma_w\{H_w(1-\cot i_2\tan\beta) + \tan\beta[H_2X - x]\}$		0	N.R.	0
P_4	$\gamma_w\alpha$	0		$\gamma_w\alpha$	0		N.R.	0
A_T	$[1/\sin\beta]\{A-B\}$			$[1/\sin\beta]\{B-A\}$			$[1/\sin\beta]\{B-A\}$	
A_1	$A_1+A_2 = \frac{1}{\sin\beta}\{H_2\cot i_2\tan\beta + x\tan\beta - A\}$		N.R.	$A_1+A_2 = 1/\sin\beta\{H_2\cot i_2\tan\beta + x\tan\beta - A\}$		N.R	$(A_1+A_2) = 1/\sin\beta\{B-A\}$	N.R
A_2			N.R.			N.R		N.R.
A_3	$[1/\sin\beta]\{\cot i_1\tan\beta(H_w - H_2)\}$		N.R.	$[1/\sin\beta]\{\cot i\tan\beta(H_w - H_2)\}$		N.R.	N.R.	
A_4	$[1/\sin\beta]\{B-\tan\beta[H_w\cot i_1 + H_2\cot i_2 + x]\}$	$\frac{1}{\sin\beta}\{\tan\beta[H_2(\cot i_1 - \cot i_2) - H_w\cot i_1 - x] + H_w\}$	N.R.	$\frac{1}{\sin\beta}\{B+\tan\beta[H_2X - H_w\cot i_1 - x]\}$	$\frac{1}{\sin\beta}\{\tan\beta[H_2(\cot i_1 - \cot i_2) - H_w\cot i_1 - x] + H_w\}$	N.R.	N.R.	
U	$1/2\{(A_1+A_2)(P_0+P_2) + A_3(P_2+P_3) + A_4(P_3+P_4)\}$		0	$1/2\{(A_1+A_2)(P_0+P_2) + A_3(P_2+P_3) + A_4(P_3+P_4)\}$		0	$1/2\{(A_1+A_2)(P_2+P_3)\}$	0
V	$\frac{\gamma_w}{2}\alpha^2$	0		$\frac{\gamma_w}{2}\alpha^2$	0		$\gamma_w \alpha^2/2$	0
Y	$T \cdot Z_{n+1}$			$T\{Z_{n+1}(1+\cot\beta\tan i_1) - H_1(1+\cot\beta\tan i_1) + H_2\tan i_1(\cot\beta + \cot i_2) - x\tan i_1\}$			$T\{Z_{n+1} - H_2\}$	

CASE ⇒	C1 (a)	C1 (b)	C1 (c)	C2 (a)	C2 (b)	C2 (c)	D1 (a)	D1 (b)
n th crack position	IN THE UPPER SLOPE			IN THE UPPER SLOPE			IN THE CREST	
n th crack condition	$H_2\cot i_2 + x < \{K_1+K_2 \ldots K_n\} < H_2\cot i_2 + x + H_1\cot i_1$			$H_2\cot i_2 + x < \{K_1+K_2 \ldots K_n\} < H_2\cot i_2 + x + H_1\cot i_1$			$H_2\cot i_2 + x + H_1\cot i_1 < \{K_1+K_2 \ldots K_n\} < (H_1+H_2)\cot\beta$	
(n+1)th position	IN THE CREST			IN THE UPPER SLOPE			IN THE CREST	
(n+1)th condition	$H_2\cot i_2 + x + H_1\cot i_1 - A\cot\beta < K_{n+1} < (H_1+H_2)\cot\beta - A\cot\beta$			$0 < K_{n+1} < H_2\cot i_2 + x + H_1\cot i_1 - A\cot\beta$			$0 < K_{n+1} < (H_1+H_2)\cot\beta - A\cot\beta$	
Weight Wedge W	$\frac{\gamma}{2}\{H_1^2\cot i_1 + 2H_1(B\cot\beta - H_1\cot i_1 - x - H_2\cot i_2) - (A\cot\beta - x - H_2\cot i_2)^2\tan i_1 - (B-H_2)^2\cot\beta - (A-H_2)^2\cot\beta\}$			$\frac{\gamma}{2}\{\tan i_1[(B\cot\beta - H_2\cot i_2 - x)^2 - (A\cot\beta - H_2\cot i_2 - x)^2] - \cot\beta[(B-H_2)^2 - (A-H_2)^2]\}$			$\frac{\gamma}{2}\{\cot\beta(Z_n^2 - Z_{n+1}^2)\}$	
* Water Table position	ABOVE BOTTOM (n+1)	BELOW (n+1)/ABOVE n TOP	BELOW n TOP	ABOVE (n+1) BOTTOM	BELOW (n+1)/ABOVE n TOP	BELOW n TOP	ABOVE (n+1) BOTTOM	BELOW (n+1)
* Water Table condition	$H_w > B$	$B > H_w > R$	$H_w < R$	$H_w > B$	$B > H_w > R$	$H_w < R$	$H_w > B$	$H_w < B$
P_0	N.R.			N.R.			N.R.	
P_1	N.R.			N.R.			N.R.	
P_2	0			0			0	
P_3	$\gamma_w\{H_2\tan\beta X - x\tan\beta + H_w(1-\cot i_1\tan\beta)\}$		0	$\gamma_w\{H_2\tan\beta X - x\tan\beta + H_w(1-\cot i_1\tan\beta)\}$		0	N.R.	
P_4	$\gamma_w\alpha$	0		$\gamma_w\alpha$	0		$\gamma_w\alpha$	0
A_T	$[1/\sin\beta]\{B-A\}$			$[1/\sin\beta]\{B-A\}$			$[1/\sin\beta]\{B-A\}$	
A_1	N.R.			N.R.			N.R.	
A_2	N.R.			N.R.			N.R.	
A_3	$[1/\sin\beta]\{H_w\cot i_1\tan\beta + x\tan\beta - A - H_2\tan\beta X\}$		N.R.	$\frac{1}{\sin\beta}\{H_w\cot i_1\tan\beta + x\tan\beta - A - H_2\tan\beta X\}$		N.R.	$(A_3+A_4) = [1/\sin\beta](K_{n+1}\tan\beta)$	N.R.
A_4	$[1/\sin\beta]\{B - H_2\tan\beta(\cot i_1 - \cot i_2) - H_w\cot i_1\tan\beta - x\tan\beta\}$	$\frac{1}{\sin\beta}\{\tan\beta[H_2(\cot i_1 - \cot i_2) - H_w\cot i_1 - x] + H_w\}$	N.R.	$\frac{1}{\sin\beta}\{B - H_w(\cot i_1 - \cot i_2)\tan\beta - x\tan\beta - H_2\cot i_2\tan\beta\}$	$\frac{1}{\sin\beta}\{\tan\beta[H_2(\cot i_1 - \cot i_2) - H_w\cot i_1 - x] + H_w\}$	N.R.		N.R.
U	$1/2\{(P_2+P_3)A_3 + (P_3+P_4)A_4\}$			$1/2\{(P_2+P_3)A_3 + (P_3+P_4)A_4\}$			$1/2\,(A_3+A_4)(P_3+P_4)$	0
V	$\gamma_w \alpha^2/2$	0		$\gamma_w/2\,\alpha^2$	0		$\gamma_w \alpha^2/2$	0
Y	$T\ Z_{n+1}$			$T\{Z_{n+1}(1-\tan i_1\cot\beta) + \tan i_1[(H_1+H_2)\cot\beta - H_1\cot i_1 - x - H_2\cot i_2]\}$			$T\ Z_{n+1}$	

* Extra Statements Re Water Table

Cases B2 & C2 : When $H_w > H_2(1-\cot i_2\tan i_1) + B\cot\beta\tan i_1 - x\tan i_1$ put H_w = this value

Cases B3 : When $H_w > H_2$ put $H_w = H_2$

WHERE $R = A(1+\cot\beta\tan i_1) - x\tan\beta - H_2\cot i_2\tan\beta$

$X = (\cot i_1 - \cot i_2)$

$B = (\cot i_1 + \cot i_2)$

6. Computer Program Logic

Figure 13 gives a schematic diagram of the computer program logic. (This figure is in the envelope inside the rear cover)

The program listing, operation manual and some example runs are given in Volume II of this report.

Volume III examines sensitivities to various parameters and details the case histories and other example analyses.

7. References

(1) "Pit Slope Manual - Supplement 5.1 - Plane Shear Analysis", Mining Research Laboratories, CANMET, Dept. EMR, Ottawa, CANMET Report 77-16.

APPENDIX 1

DETAILED CASE CALCULATIONS

APPENDIX 1

Detailed Calculations of the wedge weight W, uplift force U, horizontal thrust V and restraining force Y for the 30 cases given in the main text

Nomenclature

H_1 - height of the upper slope - ft
H_2 - height of the lower slope - ft
H_w - height of the water table - ft
i_1 - angle of the upper slope with the horizontal - degrees
i_2 - angle of the lower slope with the horizontal - degrees
x - bench width - ft
β - angle of the failure plane with the horizontal - degrees
Z_n - depth of the n th crack below surface - ft
Z_{n+1} - depth of the (n+1)th crack below the surface - ft
K_n - horizontal distance between the (n-1) th and n th cracks - ft $= 1(Z_{n-1} - Z_n)$ Cot 1.
K_{n+1} - horizontal distance between the n th and (n+1) th cracks - ft $= 1\ (Z_n - Z_{n+1})$ cot $\beta 1$
A = $H_1 + H_2 - Z_n$ - ft
B = $H_1 + H_2 - Z_{n+1}$ - ft
α = $Z_{n+1} + H_w - H_1 - H_2$
W = Weight of the failed block between n th and (n+1) th cracks - lbs
γ = Density of the rock in the failed block - lbs/cu.ft.
γ_w = Density of water - lbs/cu.ft.
P_0 = Water pressure at the bottom of the n th tension c rack. lbs/sq.ft.
P_1 = Maximum water pressure acting on the failed plane under the lower slope - lb/sq.ft.
P_2 = Water pressure acting on the failed plane under the toe of the upper slope/or as indicated on the appropriate case figure - lbs/sq.ft.
P_3 = Maximum water pressure acting on the failed plane under the upper slope - lbs/sq.ft.
P_4 = Water pressure at the bottom fo the (n+1) th tension crack, or the minimum water pressure (=0) at the intersection of the water table with the failure plane under the upper slope - lbs/sq.ft.
A_T = Total area of the failure plane between the n th and (n+1) th cracks - sq. ft.
A_1 = Area of the failure plane between the pressure P_0 and P_1 - sq. ft.
A_2 = Area of the failure plane between the pressures P_1 and P_2 - sq. ft.
A_3 = Area of the failure plane between the pressures P_2 and P_3 - sq. ft.
A_4 = Area of the failure plane between the pressures P_3 and P_4 - sq. ft.
U = Total uplift force due to water pressure acting on the failing plane between the n th and (n+1) th cracks - lbs.
V = Force applied to the failed block between the n th and (n+1) th cracks by water in the (n+1) th crack. lbs.
Y = Resisting force due to the tensile strength across the potential (n+1) th crack - lbs = $T\ Z_{(n+1)}$
T = Tensile strenght of the rock - lbs/sq.ft.
R = Total force resisting failure - lbs. $= cA_T + \tan\phi(W\cos\beta - U - V\sin\beta + Y\sin\beta)$
c = cohesion on the failure plane - lbs/sq.ft.
ϕ = Angle of friction on the failure plane - degrees.

It is assumed that the water table is perched on the impervious failure plane and that the water table is horizontal (i.e. H_w is a constant across the section). In practice there is likely to be a drawdown of the water table close to the slope face. Thus this analysis is an "extreme case" in which no drawdown of the water table is assumed and will be less stable than the drawdown case.

Case Coding

Table 4 defines the possible positions of the n th and (n+1) th cracks and the water table position for each of the 30 cases to be considered and gives the systematic code numbering system used to define these cases.

The detailed calculations for each case now follows, in accordance with this coding system.

TABLE 4: CASE CODES

Position of n th crack	Position of (n+1) crack		Position of Water Table	Case Code
A. In Lower Slope	1. In Crest	(a)	Above (n+1) crack bottom	A.1.a.
		(b)	Below (n+1) crack bottom/above H_2	A.1.b.
		(c)	Below H_2/Above n th crack top	A.1.c.
		(d)	Below n th crack top	A.1.d.
	2. In Upper Slope	(a)	Above (n+1) crack bottom	A.2.a.
		(b)	Below (n+1) crack bottom/above H_2	A.2.b.
		(c)	Below H_2/above n th crack top	A.2.c.
		(d)	Below n th crack top	A.2.d.
	3. In Bench	(a)	Above (n+1) crack bottom	A.3.a.
		(b)	Below (n+1) crack bottom/above n th crack top	A.3.b.
		(c)	Below n th crack top	A.3.c.
	4. In Lower Slope	(a)	Above (n+1) crack bottom	A.4.a.
		(b)	Below (n+1) crack bottom/above n th crack top	A.4.b.
		(c)	Below n th crack top	A.4.c.
B. In Bench	1. In Crest	(a)	Above (n+1) crack bottom	B.1.a.
		(b)	Below (n+1) crack bottom/above H_2	B.1.b.
		(c)	Below H_2 (i.e. Below n th crack top)	B.1.c.
	2. In Upper Slope	(a)	Above (n+1) crack bottom	B.2.a.
		(b)	Below (n+1) crack bottom/above H_2)	B.2.b.
		(c)	Below H_2 (i.e. Below n th crack top)	B.2.c.
	3. In Bench	(a)	Above (n+1) crack bottom	B.3.a.
		(b)	Below (n+1) crack bottom	B.3.b.
C. In Upper Slope	1. In Crest	(a)	Above (n+1) crack bottom	C.1.a.
		(b)	Below (n+1) crack bottom/above n th crack top	C.1.b.
		(c)	Below n th crack top	C.1.c.
	2. In Upper Slope	(a)	Above (n+1) crack bottom	C.2.a.
		(b)	Below (n+1) crack bottom/above n th crack top	C.2.b.
		(c)	Below n th crack top	C.2.c.
D. In Crest	1. In Crest	(a)	Above (n+1) crack bottom	D.1.a.
		(b)	Below (n+1) crack bottom	D.1.b.

CASE A.1.a.

Figure 14 illustrates this case, gives some of the relevant geometric dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(i) n th crack in the lower slope:-

$$0 < \left(K_1 + K_2 ---- + K_n\right) < H_2 \cot i_2$$

(ii) (n+1) th crack in the crest:-

$$A \cot \beta + K_{n+1} > H_2 \cot i_2 + x + H_1 \cot i_1$$

$$\text{i.e. } K_{n+1} > H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$$

and $K_{n+1} < (H_1 + H_2) \cot \beta - A \cot \beta$

2. Conditions for the water table position

Water table above the bottom of the (n+1) th crack:-

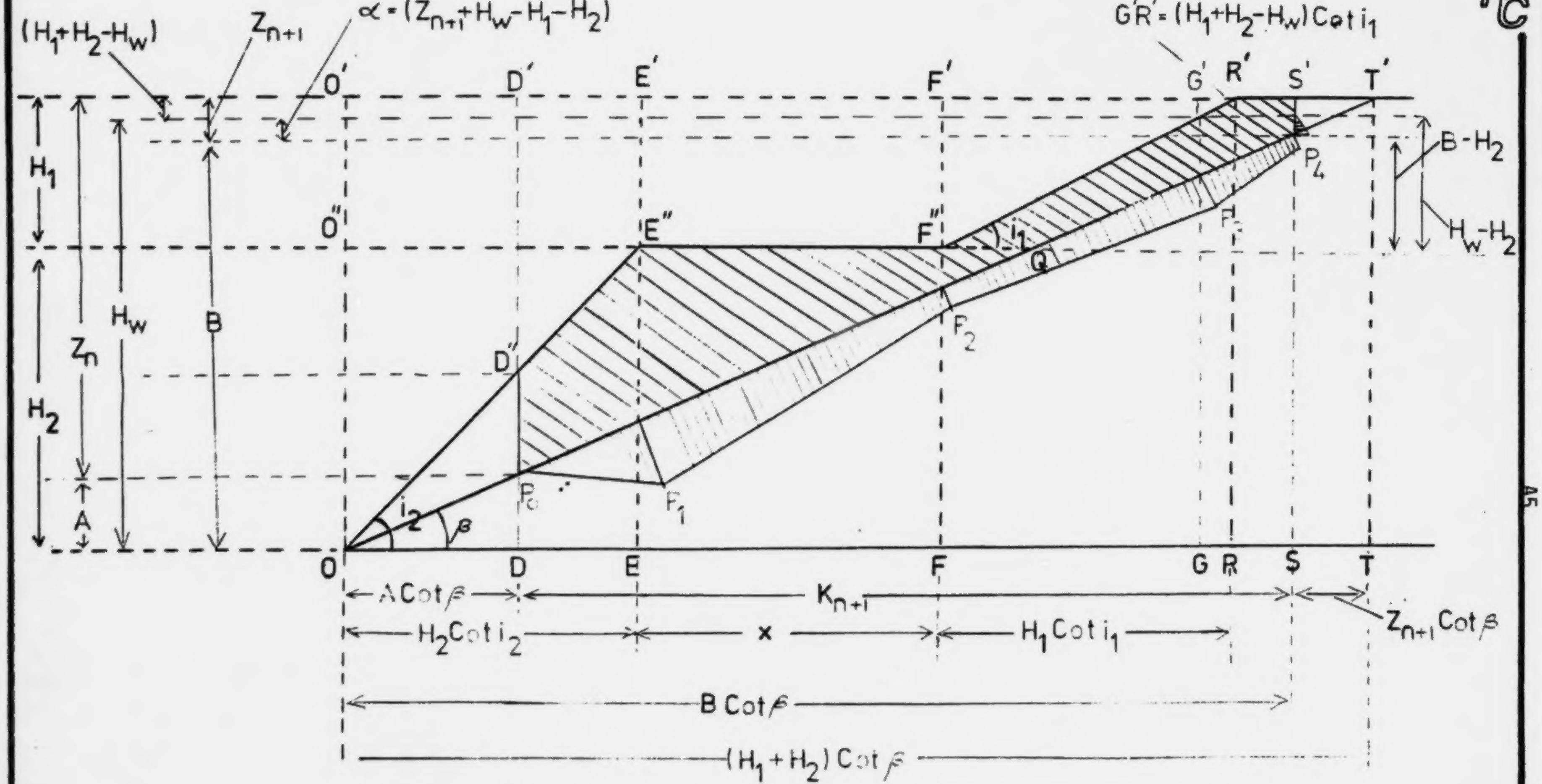
$Z_{n+1} > H_1 + H_2 - H_w$ i.e. $H_w > B$

3. Weight of the wedge, W

$$W = \left(\gamma \ OO'T' - ODD'' + ODP_0 - OO''E'' - O''O'E''E' - E'E''F''F' - F''F'R' - S'P_4T'\right)$$

$$= \gamma \left(\tfrac{1}{2} (H_1 + H_2)^2 \cot \beta - \tfrac{1}{2} A^2 \cot^2 \beta \tan i_2 + \tfrac{1}{2} A^2 \cot \beta - \tfrac{1}{2} H_2^2 \cot i_2 - H_1 H_2 \cot i_2 - H_1 x - \tfrac{1}{2} H_1^2 \cot i_1 - \tfrac{1}{2} A_{n+1}^2 \cot \beta\right)$$

i.e. $$W = \frac{\gamma}{2} \left(\cot \beta \left[(H_1 + H_2)^2 - Z_{n+1}^2\right] + A^2 \cot \beta \left[1 - \cot \beta \tan i_2\right] - \cot i_2 \left[H_1 + H_2\right]^2 - H_1^2 \left[\cot i_1 - \cot i_2\right] - 2 H_1 x\right)$$



$(H_1+H_2-H_w)$
Z_{n+1}
$\alpha=(Z_{n+1}+H_w-H_1-H_2)$
$G'R'=(H_1+H_2-H_w)\cot i_1$
O'
D'
E'
F'
G'
R'
S'
T'
H_1
H_2
Z_n
H_w
B
A
O''
E''
F''
D''
i_1
Q
P_3
P_4
P_2
P_0
P_1
i_2
β
B-H_2
H_w-H_2
O
D
E
F
G
R
S
T
$A\cot\beta$
K_{n+1}
$Z_{n+1}\cot\beta$
$H_2\cot i_2$
x
$H_1\cot i_1$
$B\cot\beta$
$(H_1+H_2)\cot\beta$

$A = H_1+H_2-Z_n$

$B = H_1+H_2-Z_{n+1}$

$\alpha = Z_{n+1}+H_w-H_1-H_2$

CASE A1 a

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG:14

4. **Pressures**

$$\underline{P_4 = \gamma_w \cdot \alpha}$$

$$P_3 = \gamma_w \left\{\tan\beta \; [G'T'] - \tan i_1 \; [G'R']\right\}$$

$$= \gamma_w \left\{\tan\beta \; [G'R' + R'T'] - G'R' \tan i_1\right\}$$

$$= \gamma_w \left\{G'R' \; (\tan\beta - \tan i_1) + R'T' \tan\beta\right\}$$

$$= \gamma_w \left\{(H_1 + H_2 - H_w) \cot i_1 \; (\tan\beta - \tan i_1) + \tan\beta \; \left((H_1 + H_2) \cot\beta - H_2 \cot i_2 - x - H_1 \cot i_1\right)\right\}$$

$$= \gamma_w \left\{(H_1 + H_2 - H_w) \cot i_1 \tan\beta - H_1 - H_2 + H_w + H_1 + H_2 - \tan\beta \; (H_2 \cot i_2 + x + H_1 \cot i_1)\right\}$$

$$\underline{P_3 = \gamma_w \left\{H_w + \tan\beta \left[H_2 (\cot i_1 - \cot i_2) - H_w \cot i_1 - x\right]\right\}}$$

$$P_2 = \gamma_w \left\{H_2 - (H_2 \cot i_2 + x) \tan\beta\right\}$$

$$= \underline{\gamma_w \left\{H_2 (1 - \cot i_2 \tan\beta) - x \tan\beta\right\}}$$

$$\underline{P_1 = \gamma_w \left\{H_2 - H_2 \cot i_2 \tan\beta\right\} = \gamma_w H_2 \left\{1 - \cot i_2 \tan\beta\right\}}$$

$$\underline{P_0 = 0}$$

5. **Areas**

$$\underline{A_T = \frac{1}{\sin\beta} (B - A)}$$

$$A_4 = \frac{G'S'}{\cos\beta} = \frac{G'S' \tan\beta}{\sin\beta} = \frac{\tan\beta}{\sin\beta}\left\{G'R' + R'T' - S'T'\right\}$$

$$= \frac{1}{\sin\beta} \left\{ \tan\beta \left[H_1 \cot i_1 + H_2 \cot i_1 - H_w \cot i_1 + H_1 \cot\beta + H_2 \cot\beta - H_2 \cot i_2 - x - H_1 \cot i_1 - Z_{n+1} \cot\beta \right] \right\}$$

$$= \frac{1}{\sin\beta} \left\{ (H_1 + H_2 - Z_{n+1}) + \tan\beta \left[H_2 (\cot i_1 - \cot i_2) - H_w \cot i_1 - x \right] \right\}$$

$$\underline{= \frac{1}{\sin\beta} \left\{ B + \tan\beta \left[H_2 (\cot i_1 - \cot i_2) - H_w \cot i_1 - x \right] \right\}}$$

$$A_3 = F'G' \frac{\tan\beta}{\sin\beta} = \frac{1}{\sin\beta} \left\{ \tan\beta \left[F'R' - G'R' \right] \right\}$$

$$= \frac{1}{\sin\beta} \left\{ \tan\beta \left[H_1 \cot i_1 - (H_1 + H_2 - H_w) \cot i_1 \right] \right\}$$

$$\underline{= \frac{1}{\sin\beta} \left\{ (H_w - H_2) \cot i_1 \tan\beta \right\}}$$

$$\underline{A_2 = \frac{\tan\beta}{\sin\beta} \left[E'F' \right] = \frac{1}{\sin\beta} \left\{ x \tan\beta \right\}}$$

$$\underline{A_1 = \frac{\tan\beta}{\sin\beta} \left[D\,E \right] = \frac{1}{\sin\beta} \left\{ \tan\beta\, (H_2 \cot i_2 - A \cot\beta) \right\} = \frac{1}{\sin\beta} \left\{ H_2 \cot i_2 \tan\beta - A \right\}}$$

6. Uplift Force, U

$$\underline{U = \left\{ \frac{P_3 + P_4}{2} \right\} A_4 + \left\{ \frac{P_2 + P_3}{2} \right\} A_3 + \left\{ \frac{P_2 + P_1}{2} \right\} A_2 + \left\{ \frac{P_1 + P_0}{2} \right\} A_1}$$

7. Horizontal Force, V, due to water in tension crack

$$\underline{V = \frac{P_4}{2} \alpha = \frac{\gamma_w}{2} \alpha^2}$$

8. Resisting Force, Y, due to tensile strength across potential crack

$$\underline{Y = T\, Z_{n+1}}$$

Table 3 summarizes the formulae for this case.

CASE A.1.b.

Figure 15 illustrates this case, gives some of the relevant geometrical dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(i) n th crack in the lower slope:-

$$0 < K_1 + K_2 ---- + K_n < H_2 \cot i_2$$

(ii) (n+1) th crack in the crest:-

$$K_{n+1} > H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$$

and $K_{n+1} < (H_1 + H_2) \cot \beta - A \cot \beta$

2. Conditions for the water table

(i) Below bottom of (n+1) th crack $Z_{n+1} < H_1 + H_2 - H_w$ i.e. $H_w < B$

(ii) Above H_2 $(H_w - H_2) > 0$ i.e. $H_w > H_2$

3. Weight of wedge, W

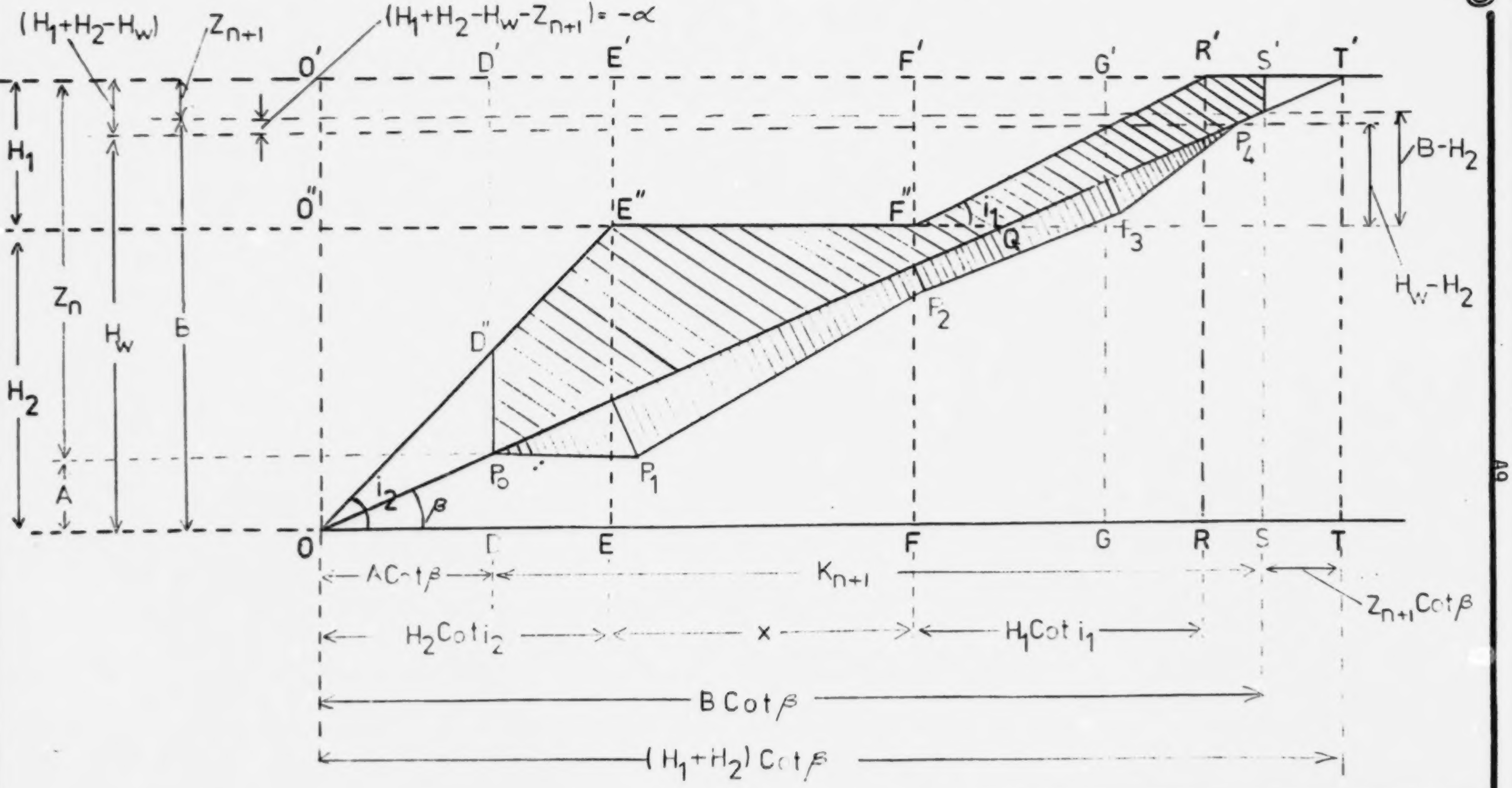
This is the same as case A.1.a. and is thus given by:-

$$W = \frac{\gamma}{2} \left\{ \cot \beta \left[(H_1 + H_2)^2 - Z_{n+1}{}^2 \right] + A^2 \cot \beta \left[1 - \cot \beta \tan i_2 \right] - \cot i_2 \left[H_1 + H_2 \right]^2 - H_1{}^2 (\cot i_1 - \cot i_2) - 2 H_1 x \right\}$$

4. Pressures

$P_4 = 0$

$$P_3 = \gamma_w \left\{ G'T' \tan \beta - G'R' \tan i_1 \right\}$$


$(H_1+H_2-H_w)$
Z_{n+1}
$(H_1+H_2-H_w-Z_{n+1}) = -\alpha$
O'
D'
E'
F'
G'
R'
S'
T'
H_1
Z_n
H_w
B
H_2
A
O''
E''
F''
D''
i_1
Q
F_3
P_4
$B-H_2$
H_w-H_2
F_2
P_0
P_1
i_2
β
O
D
E
F
G
R
S
T
$AC{\cdot}t\beta$
K_{n+1}
$Z_{n+1}\cot\beta$
$H_2\cot i_2$
x
$H_1\cot i_1$
$B\cot\beta$
$(H_1+H_2)\cot\beta$

CASE A1 b

DWN. BY : K.B.

DATE :

SCALE : -

DWG. No. : FIG: 15

$$= \gamma_w \ \{\tan \beta \ [G'R' + R'T'] \ - G'R' \ \tan i_1\}$$

$$= \gamma_w \ \{G'R' \ [\tan \beta - \tan i_1] + \tan \beta \ [(H_1 + H_2) \cot \beta] \ - (H_2 \cot i_2 + x + H_1 \cot i_1)\}$$

$$= \gamma_w \ \{(H_1 + H_2 - H_w) \cot i_1 \ (\tan \beta - \tan i_1) + H_1 + H_2 - \tan \beta \ (H_2 \cot i_2 + x + H_1 \cot i_1)\}$$

$$\underline{P_3 = \gamma_w \ \{H_w + \tan \beta \, [H_2 \ (\cot i_1 - \cot i_2) - H_w \cot i_1 - x]\}}$$

$$\underline{P_2} = \gamma_w \ \{H_2 - \tan \beta \ (H_2 \cot i_2 + x)\} \ = \underline{\gamma_w \ \{H_2 \ (1 - \cot i_2 \tan \beta) - x \tan \beta\}}$$

$$\underline{P_1 = \gamma_w H_2 \ (1 - \cot i_2 \ \tan \beta)}$$

$$\underline{P_0 = 0}$$

5. Areas

$$\underline{A_T = \frac{1}{\sin \beta} \ \{B - A\}}$$

$$A_4 = \frac{1}{\cos \beta} \ \{G'T' - S'T' - L'S'\} \ = \frac{1}{\cos \beta} \ \{G'R' + R'T' - S'T' - L'S'\}$$

$$= \frac{1}{\sin \beta} \ \{\tan \beta \ \big[(H_1 + H_2 - H_w) \cot i_1 + (H_1 + H_2) \cot \beta - H_2 \cot i_2 \ - x - H_1 \cot i_1 - Z_{n+1} \cot \beta - (H_1 + H_2 - H_w - Z_{n+1}) \cot \beta\}$$

$$= \frac{1}{\sin \beta} \left\{ B + \tan \beta \left[H_2 (\cot i_1 - \cot i_2) - H_w \cot i_1 - x \right] - \alpha \right\}$$

$$A_3 = \frac{F'G'}{\cos \beta} = \frac{F'G'}{\sin \beta} \tan \beta = \frac{1}{\sin \beta} \left\{ F'R' - G'R' \right\} \tan \beta$$

$$= \frac{1}{\sin \beta} \left\{ H_1 \cot i_1 - (H_1 + H_2 - H_w) \cot i_1 \right\} \tan \beta$$

$$= \frac{1}{\sin \beta} \left\{ (H_w - H_2) \cot i_1 \tan \beta \right\}$$

$$A_2 = \frac{1}{\sin \beta} \left\{ x \tan \beta \right\}$$

$$A_1 = \frac{\tan \beta}{\sin \beta} \left\{ H_2 \cot i_2 - A \cot \beta \right\} = \frac{1}{\sin \beta} \left\{ H_2 \cot i_2 \tan \beta - A \right\}$$

6. Uplift Force, U

$$U = \left\{ \frac{P_3 + P_4}{2} \right\} A_4 + \left\{ \frac{P_2 + P_3}{2} \right\} A_3 + \left\{ \frac{P_2 + P_1}{2} \right\} A_2 + \left\{ \frac{P_1 + P_0}{2} \right\} A_1$$

7. Horizontal Force, V, due to water in the tension crack

$V = 0$

8. Resisting Force, Y, due to tensile strength across the potential crack

$Y = T Z_{n+1}$

Table 3 summarizes the formulae for this case.

CASE A.1.c.

Figure 16 illustrates this case, gives some of the relevant geometrical dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(i) n th crack is in the lower slope:-

$$0 < K_1 + K_2 ---- + K_n < H_2 \cot i_2$$

(ii) (n+1) th crack is in the crest:-

$$K_{n+1} > H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$$

and $K_{n+1} < (H_1 + H_2) \cot \beta - A \cot \beta$

2. Conditions for the water table

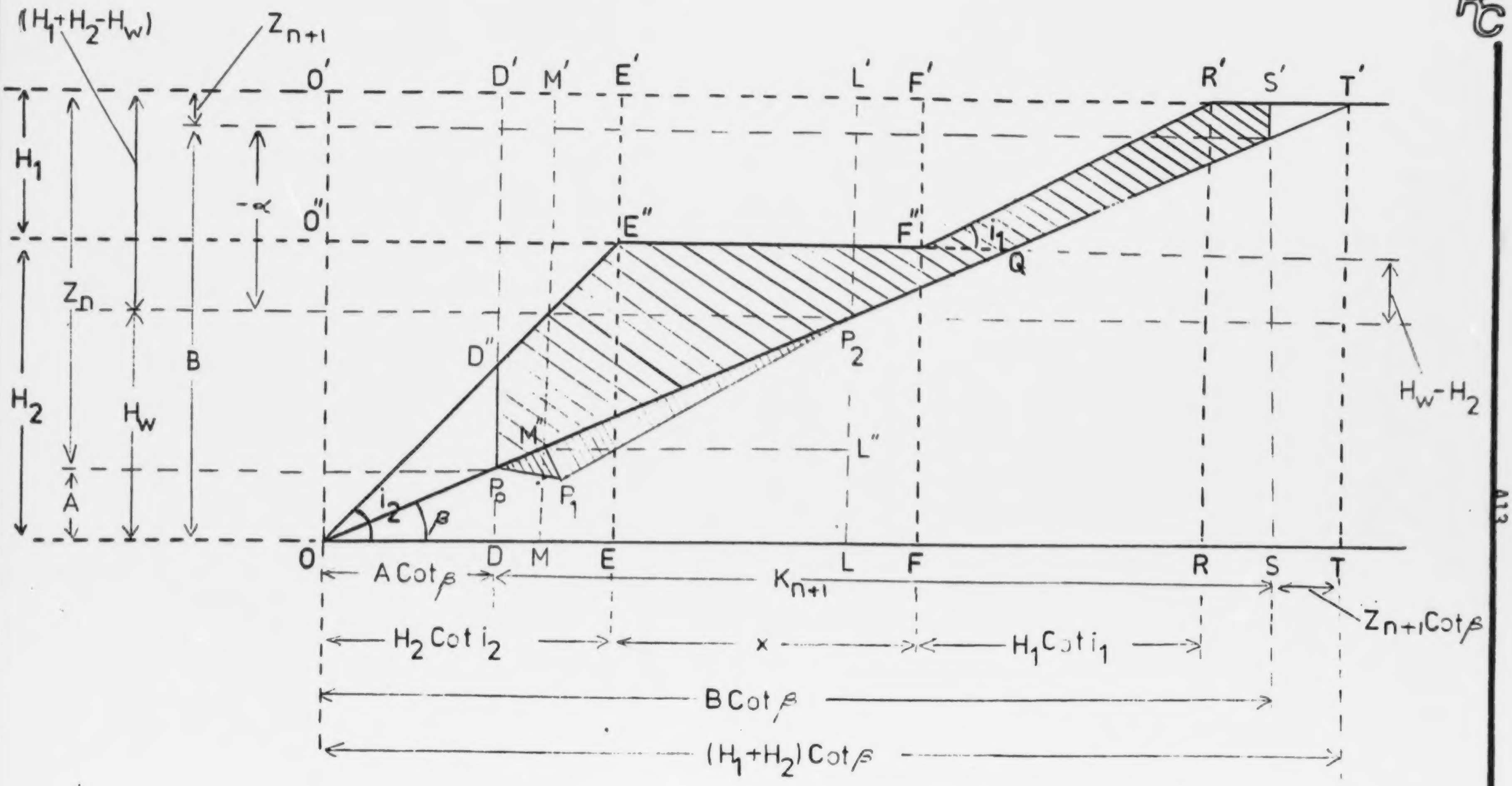
(i) Below H_2 $H_w - H_2 < 0$ i.e. $H_w < H_2$

(ii) Above top of n th crack $H_w > DD''$ i.e. $H_w \geq (A \cot \beta \tan i_2)$

3. Weight of the wedge, W

This is the same as case A.1.a. and is given by:-

$$W = \frac{\gamma}{2} \left(\cot \beta \left[(H_1 + H_2)^2 - Z_{n+1}{}^2 \right] + A^2 \cot \beta \left[1 - \cot \beta \tan i_2 \right] - \cot i_2 \left[H_1 + H_2 \right]^2 - H_1{}^2 (\cot i_1 - \cot i_2) - 2 H_1 x \right)$$



$(H_1+H_2-H_w)$
Z_{n+1}
O'
D'
M'
E'
L'
F'
R'
S'
T'
H_1
$-\alpha$
O''
E''
F''
i_1
Q
Z_n
B
D''
P_2
H_w-H_2
H_2
H_w
M''
L''
A
i_2
β
P_β
P_1
O
D
M
E
L
F
R
S
T
$A\cot\beta$
K_{n+1}
$Z_{n+1}\cot\beta$
$H_2\cot i_2$
x
$H_1\cot i_1$
$B\cot\beta$
$(H_1+H_2)\cot\beta$

CASE A1c

DWN. BY : K.B.

DATE :

SCALE : -

DWG. No. : FIG:16

4. Pressures

$$\underline{P_4 = 0}$$

$$\underline{P_3 = 0}$$

$$\underline{P_2 = 0}$$

$$P_1 = \gamma_w \left(H_w - M''M\right) = \gamma_w \left(H_w - A - DM \tan\beta\right)$$

$$= \gamma_w \left\{H_w - A - \tan\beta\,(DE - ME)\right\}$$

$$= \gamma_w \left(H_w - A - \tan\beta \left[H_2 \cot i_2 - A \cot\beta - (H_2 - H_w)\cot i_2\right]\right)$$

$$= \gamma_w \left(H_w - A - H_2 \cot i_2 \tan\beta + A + H_2 \cot i_2 \tan\beta - H_w \cot i_2 \tan\beta\right)$$

$$= \underline{\gamma_w H_w \left(1 - \cot i_2 \tan\beta\right)}$$

$$\underline{P_0 = 0}$$

5. Areas

$$\underline{A_T = \frac{1}{\sin\beta}\left(B - A\right)}$$

A_4 - not required.

A_3 - not required.

$$A_2 = \frac{P_2 L''}{\sin\beta} = \frac{1}{\sin\beta}\left(H_w - H_w \cot i_2 \tan\beta\right)$$

$$= \underline{\frac{H_w}{\sin\beta}\left(1 - \cot i_2 \tan\beta\right)}$$

$$A_1 = \frac{DM}{\cos\ \beta} = \frac{1}{\sin\ \beta}\left(DM\ \tan\ \beta\right) = \frac{1}{\sin\ \beta}\left(MM'' - A\right)$$

$$= \frac{1}{\sin\ \beta}\quad\left(H_w\ \cot\ i_2\ \tan\ \beta - A\right)$$

$$\underline{= \frac{1}{\sin\ \beta}\left(H_w\ \cot\ i_2\ \tan\ \beta - A\right)}$$

6. Uplift Force, U

$$\underline{U = \tfrac{1}{2}\left((P_3 + P_4)\ A_4 + (P_2 + P_3)\ A_3 + (P_2 + P_1)\ A_2 + (P_1 + P_0)\ A_1\right)}$$

7. Horizontal Force, V, due to water in the tension crack

$\underline{V = 0}$

8. Resisting Force, Y, due to tensile strength across the potential crack

$\underline{Y = T\ Z_{n+1}}$

Table 3 summarizes the formulae for this case.

CASE A.1.d.

Figure 17 illustrates this case, gives some of the relevant geometrical dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(i) n th crack in the lower slope:-

$$0 < \left(K_1 + K_2 ---- + K_n\right) < H_2 \cot i_2$$

(ii) (n+1) th crack in the crest:-

$$K_{n+1} > H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$$

and $$K_{n+1} < (H_1 + H_2) \cot \beta - A \cot \beta$$

2. Conditions for the water table

Water table below the top of the n th crack:- $H_w < A \cot \beta \tan i_2$

3. Weight of wedge, W

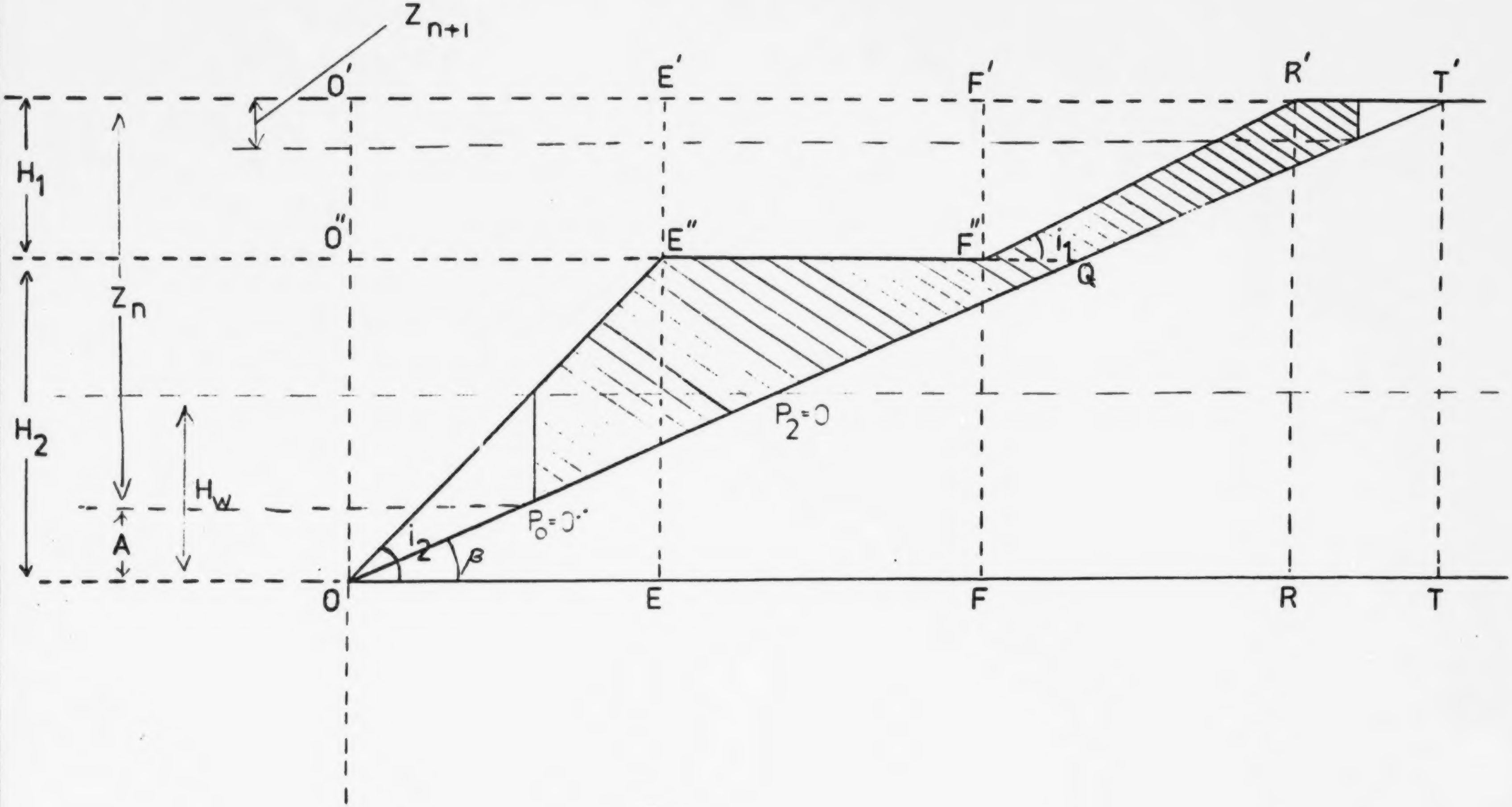
This is the same as case A.1.a. and is given by:-

$$W = \frac{\gamma}{2} \left\{\cot \beta \left[(H_1 + H_2)^2 - Z_{n+1}{}^2\right] + A^2 \cot \beta \left[1 - \cot \beta \tan i_2\right] - \cot i_2 \left[H_1 + H_2\right]^2 - H_1{}^2 (\cot i_1 - \cot i_2) - 2 H_1 x\right\}$$

4. Pressures

$P_0 = P_1 = P_2 = P_3 = P_4 = 0$

Note that when the water table intersects the top of the n th crack in the slope face, then the water pressure is a maximum. However, this value must be zero due to the n th crack. Hence there are no water pressure forces acting.


Z n+1
O'
E'
F'
R'
T'
H1
Zn
O"
E"
F"
i1
Q
H2
P2=0
Hw
A
i2
β
P0=0
O
E
F
R
T

CASE A1d	
DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG: 17

5. Areas

$$A_T = \frac{1}{\sin\beta}\left(B - A\right)$$

Areas A_1, A_2, A_3 and A_4 are not required.

6. Uplift Force, U

$U = 0$ since all pressures are zero.

7. Horizontal Force, V, due to water in the crack

$V = 0$

8. Resisting Force, Y, due to tensile strength across the potential crack

$Y = T\ Z_{n+1}$

Table 3 summarizes the formulae for this case.

CASE A.2.a.

Figure 18 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(i) n th crack in the lower slope:-

$$0 < \left\{K_1 + K_2 ---- + K_n\right\} < H_2 \cot i_2$$

(ii) (n+1) th crack in the upper slope:-

(a) $A \cot \beta + K_{n+1} < H_2 \cot i_2 + x + H_1 \cot i_1$

i.e. $K_{n+1} < H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$

and (b) $A \cot \beta + K_{n+1} > H_2 \cot i_2 + x$

i.e. $K_{n+1} > H_2 \cot i_2 + x - A \cot \beta$

$$\text{i.e. } H_2 \cot i_2 + x - A \cot \beta < K_{n+1} < H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$$

2. Conditions for the water table

Water table above the bottom of the (n+1) th crack $Z_{n+1} > (H_1 + H_2 - H_w)$

i.e. $H_w > B$

When $H_w > H_2 (1 - \cot i_2 \tan i_1) + B \cot \beta \tan i_1 - x \tan i_1$

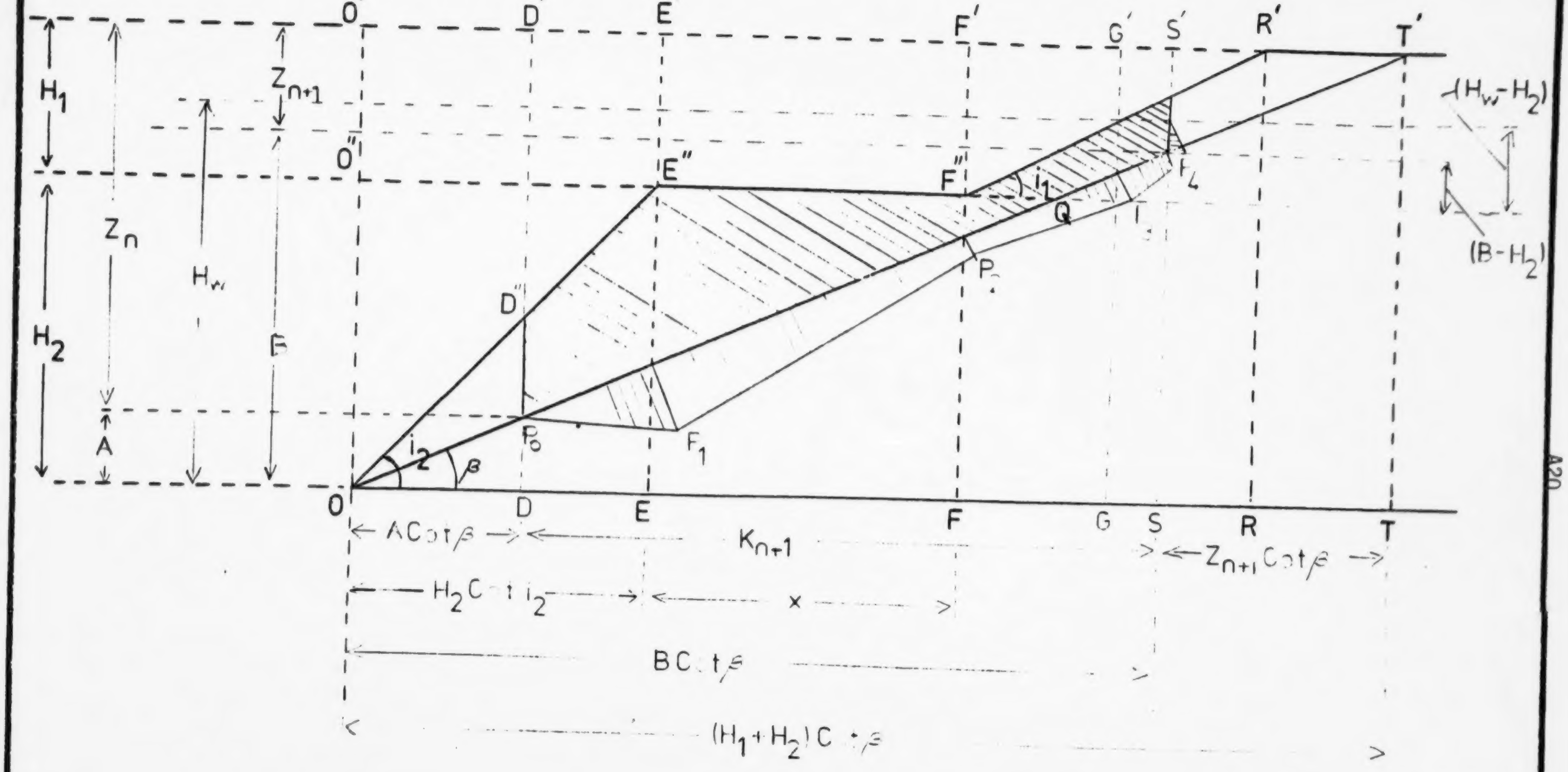
put $H_w = H_2 (1 - \cot i_2 \tan i_1) + B \text{Cot}_{\beta} \tan i_1 - x \tan i_1$

3. Weight of the wedge, W

$$W = \gamma \left\{OO'T - ODD'' + ODP_0 - OO''E'' - O'O''E''E' - E'E''F''F' - F'F''R' + S'S''R' - S'P_4T'\right\}$$

$$= \gamma \left\{ \tfrac{1}{2} (H_1 + H_2)^2 \cot \beta - \tfrac{1}{2} A^2 \cot^2\beta \tan i_2 + \tfrac{1}{2} A^2 \cot \beta - \tfrac{1}{2} H_2^2 \cot i_2 - H_1H_2 \cot i_2 - H_1 x - \tfrac{1}{2} H_1^2 \cot i_1 + \tfrac{1}{2} (S'R')^2 \tan i_1 - (Z_{n+1})^2 \cot \beta + \tfrac{1}{2} H_1^2 \cot i_2 - \tfrac{1}{2} H_1^2 \cot i_2 \right\}$$

but $S'R' = (H_2 \cot i_2 + x + H_1 \cot i_1 - B \cot \beta)$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Zn+1
Hw
B
A
i2
β
P0
F1
P2
Q
i1
F4
O
D
E
F
G
S
R
T
(Hw-H2)
(B-H2)
ACot β
Kn+1
Zn+1 Cot β
H2 Cot i2
x
BCot β
(H1+H2) Cot β

CASE A2a

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG:18

thus

$$W = \frac{\gamma}{2}\Big\{\cot\beta\left[(H_1 + H_2)^2 - Z_{n+1}{}^2\right] + A^2\cot\beta\left[1 - \cot\beta\tan i_2\right] - \cot i_2$$
$$\left[H_1 + H_2\right]^2 - H_1{}^2(\cot i_1 - \cot i_2) - 2H_1x + \tan i_1\,(S'R')^2\Big\}$$

i.e.

$$W = \frac{\gamma}{2}\Big\{\cot\beta\left[(H_1 + H_2)^2 - Z_{n+1}{}^2\right] + A^2\cot\beta\left[1 - \cot\beta\tan i_2\right] - \cot i_2$$
$$\left[H_1 + H_2\right]^2 - H_1{}^2(\cot i_1 - \cot i_2) - 2H_1x + \tan i_1\Big[H_2\cot i_2 + x$$
$$+ H_1\cot i_1 - B\cot\Big]\beta^2\Big\}$$

4. **Pressures**

$$P_4 = \gamma_w \cdot \alpha$$

$$P_3 = \gamma_w\left\{\tan\beta\,(G'T') - \tan i_1\,(G'R')\right\}$$

$$= \gamma_w\left\{\tan\beta\,(G'R' + R'T') - G'R'\tan i_1\right\}$$

$$= \gamma_w\left\{G'R'(\tan\beta - \tan i_1) + R'T'\tan\beta\right\}$$

$$= \gamma_w\Big\{(H_1 + H_2 - H_w)\cot i_1(\tan\beta - \tan i_1) + \tan\beta\Big[(H_1 + H_2)\cot\beta$$
$$- H_2\cot i_2 - x - H_1\cot i_1\Big]\Big\}$$

$$= \gamma_w\Big\{(H_1 + H_2 - H_w)\cot i_1\tan\beta - H_1 - H_2 + H_w + H_1 + H_2 - \tan\beta$$
$$(H_2\cot i_2 + x + H_1\cot i_1)\Big\}$$

i.e.

$$P_3 = \gamma_w\left\{H_w + \tan\beta\left[H_2(\cot i_1 - \cot i_2) - H_w\cot i_1 - x\right]\right\}$$

$$P_2 = \gamma_w\left\{H_2 - (H_2\cot i_2 + x)\tan\beta\right\}$$

$$= \gamma_w\left\{H_2(1 - \cot i_2\tan\beta) - x\tan\beta\right\}$$

$$P_1 = \gamma_w\left\{H_2 - H_2\cot i_2\tan\beta\right\} = \gamma_w H_2\left\{1 - \cot i_2\tan\beta\right\}$$

$$P_0 = 0$$

5. Areas

$$\underline{A_T = \frac{1}{\sin\beta}\left\{B - A\right\}}$$

$$A_4 = \frac{G'S'}{\cos\beta} = \frac{1}{\sin\beta} G'S' \tan\beta = \frac{1}{\sin\beta}\left\{\tan\beta\,(G'R' + R'T' - S'T')\right\}$$

$$= \frac{1}{\sin\beta}\left\{\tan\beta\left[H_1 \cot i_1 + H_2 \cot i_1 - H_w \cot i_1 + H_1 \cot\beta + H_2 \cot\beta - H_2 \cot i_2 - x - H_1 \cot i_1 - Z_{n+1} \cot\right]\beta\right\}$$

$$= \frac{1}{\sin\beta}\left\{(H_1 + H_2 - Z_{n+1}) + \tan\beta\left[H_2(\cot i_1 - \cot i_2) - H_w \cot i_1 - x\right]\right\}$$

$$= \underline{\frac{1}{\sin\beta}\left\{B + \tan\beta\left[H_2(\cot i_1 - \cot i_2) - H_w \cot i_1 - x\right]\right\}}$$

$$A_3 = \frac{F\,G\,\tan\beta}{\sin\beta} = \frac{1}{\sin\beta}\left\{\tan\beta\,(F'R' - G'R')\right\} = \frac{1}{\sin\beta}\left\{\tan\beta\,(H_1 \cot i_1 - (H_1 + H_2 - H_w \cot i_1))\right\}$$

$$= \underline{\frac{1}{\sin\beta}\left\{(H_w - H_2) \cot i_1 \tan\beta\right\}}$$

$$\underline{A_2 = \frac{1}{\sin\beta}\left\{x \tan\beta\right\}}$$

$$\underline{A_1} = \frac{\tan\beta}{\sin\beta}\left\{D\,E\right\} = \frac{1}{\sin\beta}\left\{\tan\beta\,(H_2 \cot i_2 - A \cot\beta)\right\} = \underline{\frac{1}{\sin\beta}\left\{H_2 \cot i_2 \tan\beta - A\right\}}$$

6. Uplift Force, U

$$\underline{U = \left\{\frac{P_3 + P_4}{2}\right\} A_4 + \left\{\frac{P_2 + P_3}{2}\right\} A_3 + \left\{\frac{P_2 + P_1}{2}\right\} A_2 + \left\{\frac{P_1 + P_0}{2}\right\} A_1}$$

7. Horizontal Force, V, due to water in the tension crack

$$\underline{V = \frac{P_4}{2} \cdot \alpha = \frac{\gamma_w}{2}\,\alpha^2}$$

8. Resisting Force, Y, due to the tensile strength across the potential crack

$$Y = T\left(Z_{n+1} - S'R' \tan i_1\right) = T\left(Z_{n+1} - \tan i_1 (H_2 \cot i_2 + x + H_1 \cot i_1 - B \cot \beta)\right)$$

$$= T\left(Z_{n+1} - \tan i_1 \left[H_2 \cot i_2 + x + H_1 \cot i_1 - H_1 \cot \beta - H_2 \cot \beta + Z_{n+1} \cot \beta\right]\right)$$

$$= T\left(Z_{n+1} (1 + \cot \beta \tan i_1) - H_1 (1 + \cot \beta \tan i_1) - H_2 \tan i_1 (\cot \beta + \cot i_2) - x \tan i_1\right)$$

Table 3 summarizes these formulae.

CASE A.2.b.

Figure 19 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(i) n th crack in the lower slope:-

$$0 < \left\{K_1 + K_2 + \text{----} K_n\right\} < H_2 \cot i_2$$

(ii) (n+1) th crack in the upper slope:-

$$H_2 \cot i_2 + x - A \cot \beta < K_{n+1} < H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$$

2. Conditions for the water table

(i) Below bottom of (n+1) th crack $Z_{n+1} < H_1 + H_2 - H_w$ i.e. $H_w < B$

(ii) Above H_2 $H_w - H_2 > 0$ i.e. $H_w > H_2$

(iii) When $H_w > H_2 (1 - \cot i_2 \tan i_1) + B \text{ Cot } \beta \tan i_1 - x \tan i_1$

put $H_w = H_2 (1 - \text{Cot } i_2 \tan i_1) + B \text{ Cot}_\beta \tan i_1 - x \tan i_1$

3. Weight of wedge, W

This is the same as case A.2.a. and is thus given by:-

$$W = \frac{\gamma}{2} \left\{\cot \beta \left[(H_1 + H_2)^2 - Z_{n+1}{}^2\right] + A^2 \cot \beta \left[1 - \cot \beta \tan i_2\right] - \cot i_2 \left[H_1 + H_2\right]^2 - H_1{}^2 (\cot i_1 - \cot i_2) - 2 H_1 x + \tan i_1 \left[H_2 \cot i_2 + x + H_1 \cot i_1 - B \cot \beta\right]^2\right\}$$

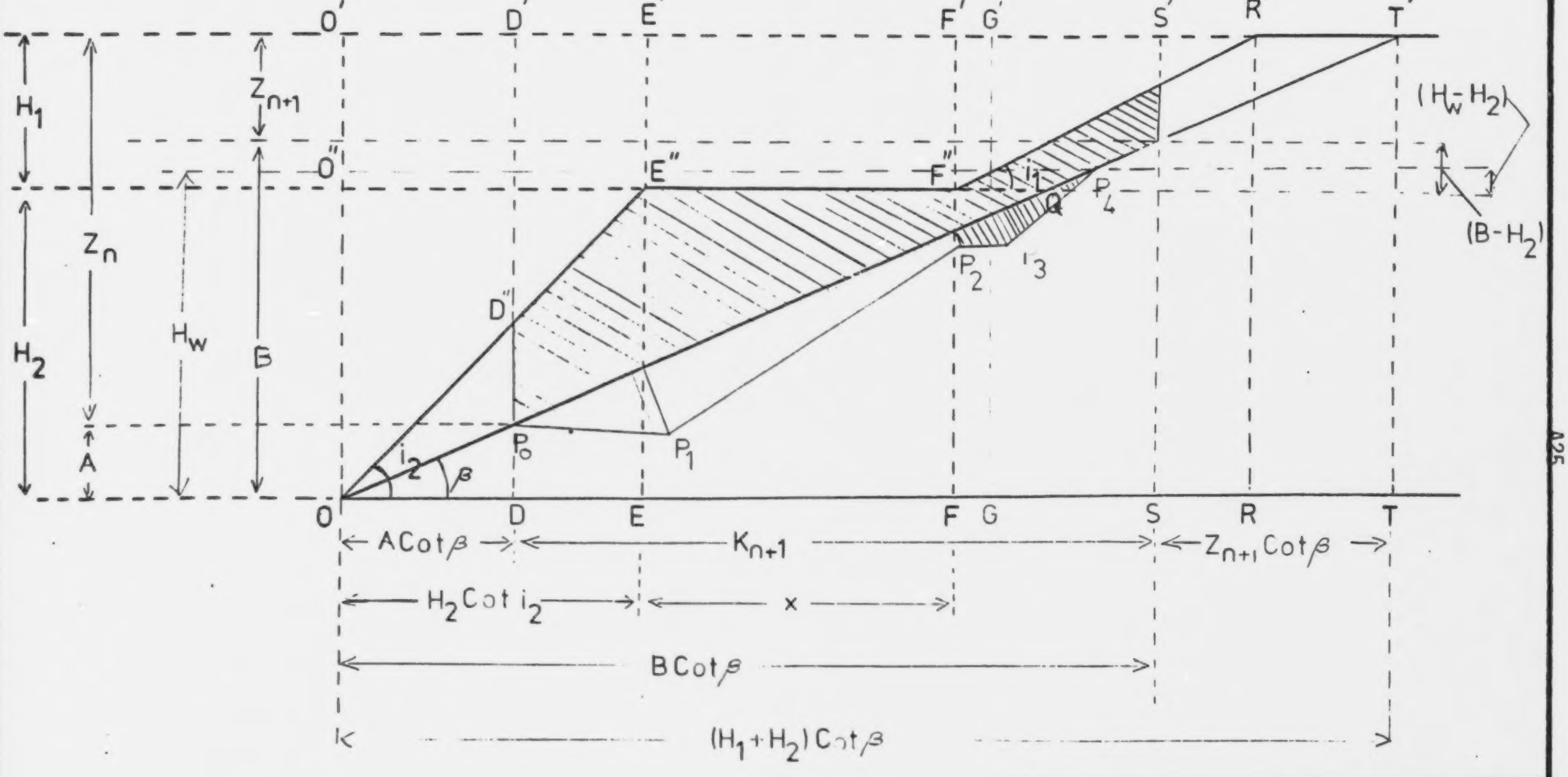
4. Pressures

$P_4 = 0$

$P_3 = \gamma_w \left\{G'T' \tan \beta - G'R' \tan i_1\right\}$ which is same as case A.1.b.

$= \gamma_w \left\{H_w + \tan \beta \left[H_2 (\cot i_1 - \cot i_2) - H_w \cot i_1 - x\right]\right\}$

$P_2 = \gamma_w \left\{H_2 - \tan \beta (H_2 \cot i_2 + x)\right\} = \gamma_w \left\{H_2 (1 - \cot i_2 \tan \beta) - x \tan \beta\right\}$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H2
Zn+1
Zn
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Hw
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A
D''
P0
P1
P2
P4
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i2
i3
β
(Hw-H2)
(B-H2)
O
D
E
F
G
S
R
T
ACotβ
Kn+1
Zn+1 Cotβ
H2Cot i2
x
BCotβ
(H1+H2) Cotβ

CASE A2b

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG: 19

$$P_1 = \gamma_w H_2 (1 - \cot i_2 \tan \beta)$$

$$P_0 = 0$$

5. Areas

$$A_T = \frac{1}{\sin \beta} \left(B - A\right)$$

$$A_4 = \frac{\tan \beta}{\sin \beta} \left[G'T' - S'T' - L'S'\right] = \frac{\tan \beta}{\sin \beta} \left[G'R' + R'T' - S'T' - L'S'\right]$$

$$= \frac{1}{\sin \beta} \Big(\tan \beta \Big[(H_1 + H_2 - H_w) \cot i_1 + (H_1 + H_2) \cot \beta - H_2 \cot i_2 - x - H_1 \cot i_1 - Z_{n+1} \cot \beta - (H_1 + H_2 - H_w - Z_{n+1}) \cot \beta\Big]\Big)$$

$$= \frac{1}{\sin \beta} \Big[H_1 \cot i_1 \tan \beta + H_2 \cot i_1 \tan \beta - H_w \cot i_1 \tan \beta + H_1 + H_2 - H_2 \cot i_2 \tan \beta - x \tan \beta - H_1 \cot i_1 \tan \beta - Z_{n+1} - H_1 - H_2 + H_w + Z_{n+1}\Big]$$

$$= \frac{1}{\sin \beta} \Big(\tan \beta \left[H_2 (\cot i_1 - \cot i_2) - H_w \cot i_1 - x\right] + H_w\Big)$$

$$A_3 = \frac{\tan \beta}{\sin \beta} \left(F'G'\right) = \frac{1}{\sin \beta} \left(\tan \beta \, (F'R' - G'R')\right)$$

$$= \frac{1}{\sin \beta} \Big(\tan \beta \left[H_1 \cot i_1 - (H_1 + H_2 - H_w) \cot i_1\right]\Big)$$

$$= \frac{1}{\sin \beta} \Big((H_w - H_2) \cot i_1 \tan \beta\Big)$$

$$A_2 = \frac{1}{\sin \beta} \left(x \tan \beta\right)$$

$$A_1 = \frac{\tan \beta}{\sin \beta} \left(H_2 \cot i_2 - A \cot \beta\right) = \frac{1}{\sin \beta} \left(H_2 \cot i_2 \tan \beta - A\right)$$

6. Uplift Force, U

$$U = \left\{\frac{P_3 + P_4}{2}\right\} A_4 + \left\{\frac{P_2 + P_3}{2}\right\} A_3 + \left\{\frac{P_1 + P_2}{2}\right\} A_2 + \left\{\frac{P_1 + P_0}{2}\right\} A_1$$

7. Horizontal Force, V, due to water in the tension crack

$V = 0$

8. Resisting Force, Y, due to tensile strength across the potential crack

$$Y = T\,(Z_{n+1} - S'R' \tan i_1) = T\left[Z_{n+1} - \tan i_1\,(H_2 \cot i_2 + x + H_1 \cot i_1 - B \cot \beta)\right]$$

$$= T\left(Z_{n+1}\,(1 + \tan i_1 \cot \beta) - H_1\,(1 + \tan i_1 \cot \beta) - H_2 \tan i_1\,(\cot \beta + \cot i_2) - x \tan i_1\right)$$

CASE A.2.c.

Figure 20 illustrates this case, gives some of the relevant dimensions, the position of the water pressures acting and the water pressure distribution.

1. Conditions for the crack positions

(i) n th crack in the lower slope:-

$$0 < \left(K_1 + K_2 + ---- K_n\right) < H_2 \cot i_2$$

(ii) (n+1) th crack in the upper slope:-

$$H_2 \cot i_2 + x - A \cot \beta < K_{n+1} < H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$$

2. Conditions for the water table

(i) Below H_2 $\qquad$ $H_2 > H_w$

(ii) Above n th crack top $\qquad$ $H_w > A \cot \beta \tan i_2$

(iii) When $H_w > H_2 (1 - \cot i_2 \tan i_1) + B \operatorname{Cot} \beta \tan i_1 - x \tan i_1$

put $H_w = H_2 (1 - \operatorname{Cot} i_2 \tan i_1) + B \operatorname{Cot}_\beta \tan i_1 - x \tan i_1$

3. Weight of the wedge, W

This is the same as case A.2.a. and is given by:-

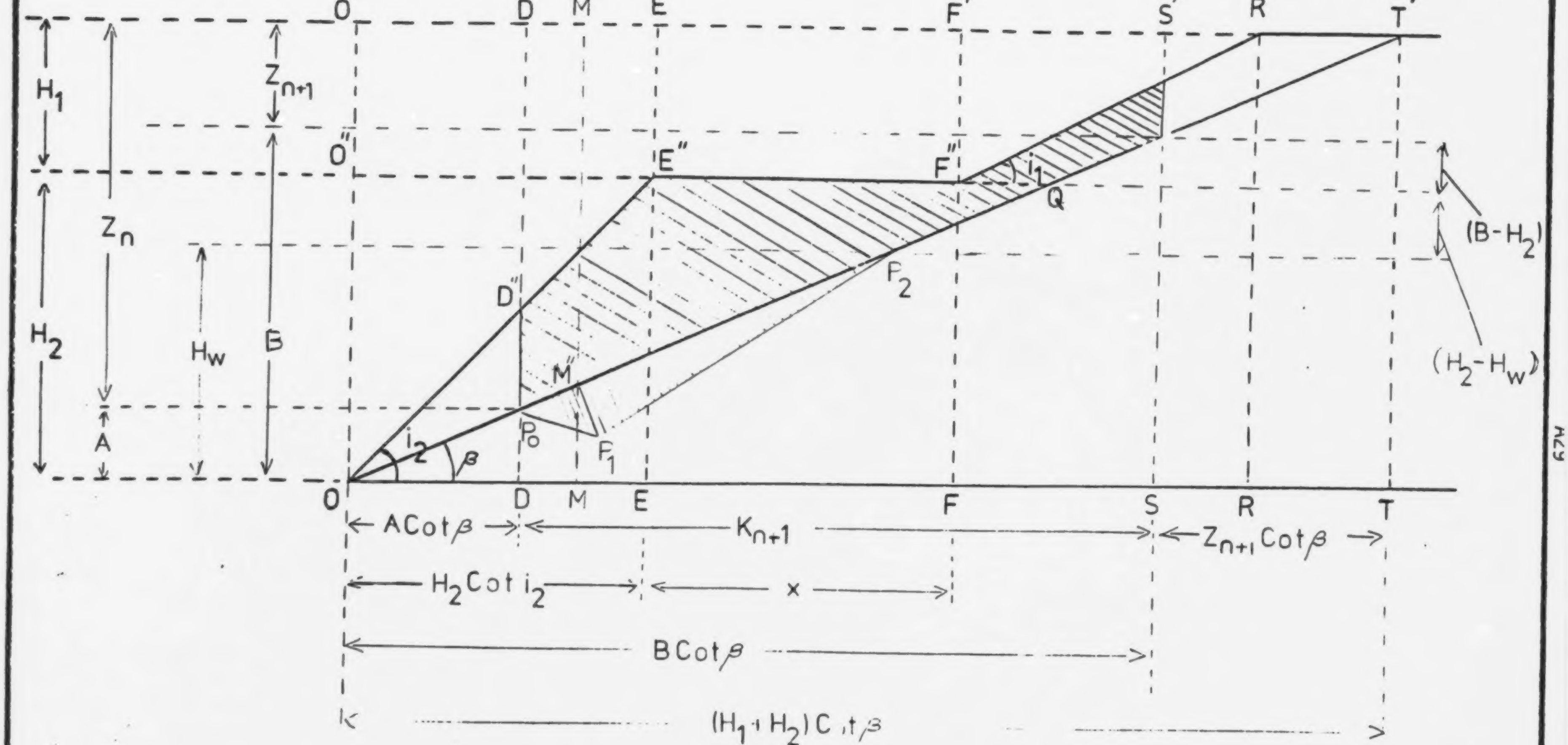
$$W = \frac{\gamma}{2} \left\{\cot \beta \left[(H_1 + H_2)^2 - Z_{n+1}{}^2\right] + A^2 \cot \beta \left[1 - \cot \beta \tan i_2\right] - \cot i_2 \left[H_1 + H_2\right]^2 - H_1{}^2 (\cot i_1 - \cot i_2) - 2 H_1 x + \tan i_1 \left[H_2 \cot i_2 + x + H_1 \cot i_1 - B \cot \beta\right]^2\right)$$

4. Pressures

$P_4 = 0$

$P_3 = 0$

$P_2 = 0$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P_0
F_1
i_2
β
O
D
M
E
F
S
R
T
H_1
H_2
Z_n
Z_{n+1}
A
H_w
B
(B-H_2)
(H_2-H_w)
A Cot β
K_{n+1}
Z_{n+1} Cot β
H_2 Cot i_2
x
B Cot β
(H_1+H_2) Cot β

CASE A2c

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG: 2

$$P_1 = \gamma_w \left(H_w - M'M\right) = \gamma_w \left(H_w - A - D\,M \tan\beta\right)$$

$$= \gamma_w \left(H_w - A - \tan\beta\,(D\,E - M\,E)\right)$$

$$= \gamma_w \left(H_w - A - \tan\beta\,(H_2 \cot i_2 - A \cot\beta - (H_2 - H_w) \cot i_2\right)$$

$$= \gamma_w \left(H_w - A - H_2 \cot i_2 \tan\beta + A + H_2 \cot i_2 \tan\beta - H_w \cot i_2 \tan\beta\right)$$

$$= \underline{\gamma_w H_w \left(1 - \cot i_2 \tan\beta\right)}$$

$$\underline{P_0 = 0}$$

5. Areas

$$\underline{A_T = \frac{1}{\sin\beta}\left(B - A\right)}$$

$\underline{A_4 \text{ - not required}}$

$\underline{A_3 \text{ - not required}}$

$$A_2 = \frac{P_2 L''}{\sin\beta} = \frac{1}{\sin\beta}\left(H_w - H_w \cot i_2 \tan\beta\right)$$

$$= \underline{\frac{H_w}{\sin\beta}\left(1 - \cot i_2 \tan\beta\right)}$$

$$A_1 = \frac{D\,M \tan\beta}{\sin\beta} = \frac{1}{\sin\beta}\left(M\,M' - A\right)$$

$$= \underline{\frac{1}{\sin\beta}\left(H_w \cot i_2 \tan\beta - A\right)}$$

6. Uplift Force, U

$$U = \tfrac{1}{2} \{ (P_3 + P_4)A_4 + (P_2 + P_3)A_3 + (P_2 + P_1)A_2 + (P_1 + P_0)A_1 \}$$

7. Horizontal Force, V, due to water in the tension crack

$$V = 0$$

8. Resisting Force, Y, due to tensile strength across the potential crack

$$Y = T \{ Z_{n+1} - S'R' \tan i_1 \} = T \{ Z_{n+1} - \tan i_1 (H_2 \cot i_2 + x + H_1 \cot i_1 - B \cot \beta) \}$$

$$= T \{ Z_{n+1} - \tan i_1 [H_2 \cot i_2 + x + H_1 \cot i_1 - H_1 \cot \beta - H_2 \cot \beta + Z_{n+1} \cot \beta] \}$$

$$= T \{ Z_{n+1} - H_2 \cot i_2 \tan i_1 - x \tan i_1 - H_1 - H_1 \cot \beta \tan i_1 - H_2 \cot \beta \tan i_1 + Z_{n+1} \cot \beta \tan i_1 \}$$

$$= T \{ Z_{n+1} [1 + \cot \beta \tan i_1] - H_1 [1 + \cot \beta \tan i_1 \quad - H_2 \tan i_1 (\cot \beta + \cot i_2)] - x \tan i_1 \}$$

Table 3 summarizes these formulae.

CASE A.2.d.

Figure 21 illustrates this case, gives some of the relevant dimensions, the position of the water pressures acting and the water pressure distribution.

1. Conditions for the crack positions

(i) n th crack in the lower slope:-

$$0 < \left(K_1 + K_2 + ---- K_n\right) < H_2 \cot i_2$$

(ii) (n+1) th crack in upper slope:-

$$H_2 \cot i_2 + x - A \cot \beta < K_{n+1} < H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$$

2. Conditions for the water table

Water table below top of the n th crack:- $H_w < A \cot \beta \tan i_2$

When $H_w > H_2 (1 - \cot i_2 \tan i_1) + B \operatorname{Cot} \beta \tan i_1 - x \tan i_1$

put $H_w = H_2 (1 - \operatorname{Cot} i_2 \tan i_1) + B \operatorname{Cot}_\beta \tan i_1 - x \tan i_1$

3. Weight of the wedge, W

This is the same as case A.2.a. and is given by:-

$$W = \frac{\gamma}{2} \left(\cot \beta \left[(H_1 + H_2)^2 - Z_{n+1}{}^2\right] + A^2 \cot \beta \left[1 - \cot \beta \tan i_2\right] - \cot i_2 \left[H_1 + H_2\right]^2 - H_1{}^2 \left[\cot i_1 - \cot i_2\right] - 2 H_1 x + \tan i_1 \left[H_2 \cot i_2 + x + H_1 \cot i_1 - B \cot \beta\right]^2\right)$$

4. Pressures

$P_0 = P_1 = P_2 = P_3 = P_4 = 0$

5. Areas

$$A_T = \frac{1}{\sin \beta} \left(B - A\right)$$

Areas A_1, A_2, A_3 and A_4 are not required.

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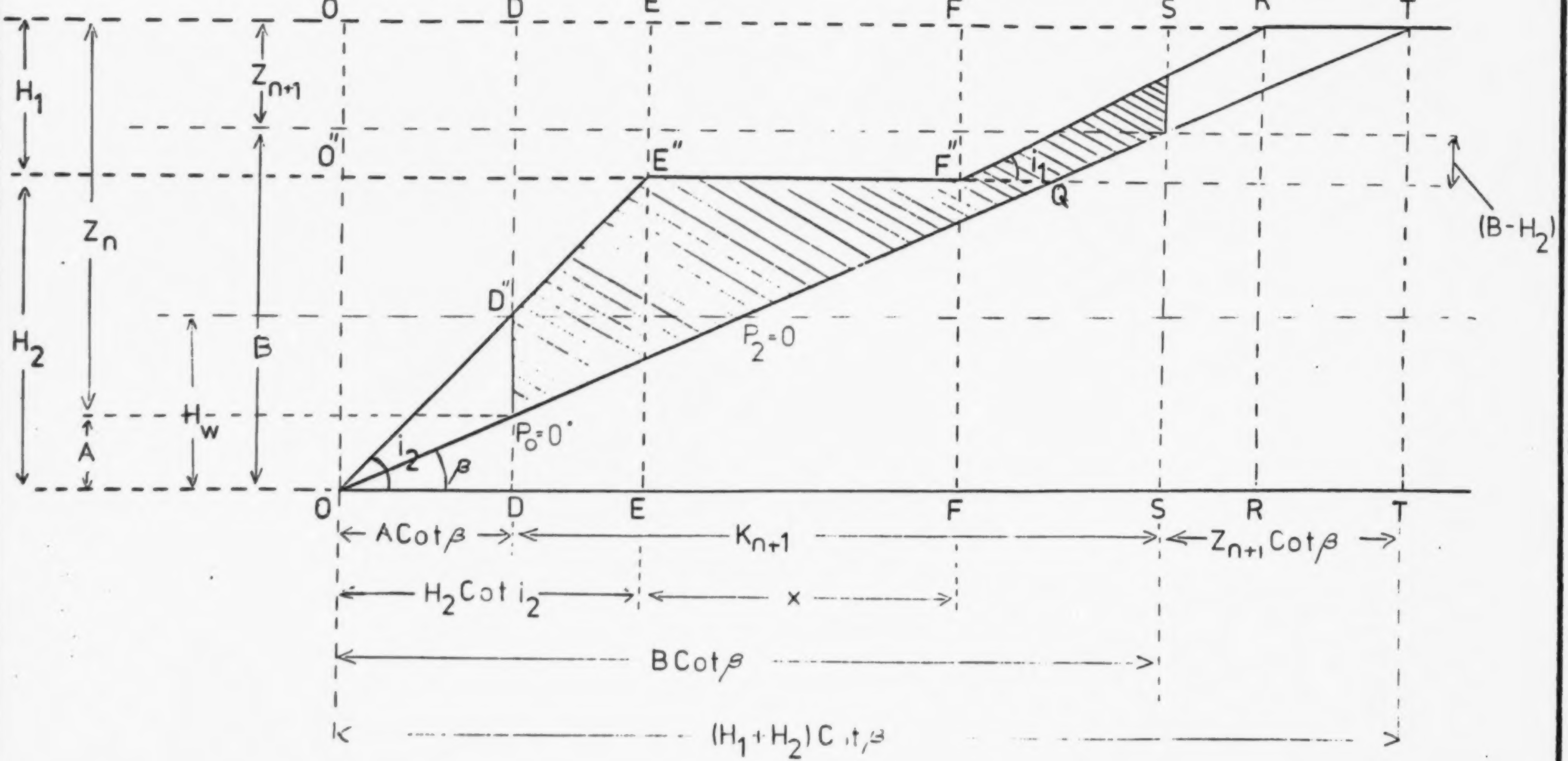
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Z n
D''
H2
B
P2=0
Hw
A
i2
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P0=0'
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R
T
← ACot β →
← K n+1 →
← Z n+1 Cot β →
← H2 Cot i2 →
← x →
← BCot β →
← (H1+H2) Cot β →

CASE A2d

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG:21

6. Uplift Force, U

   $U = 0$ since all pressures are zero

7. Horizontal Force, V, due to water in the crack

   $V = 0$

8. Resisting Force, Y, due to tensile strength across the potential crack

$$Y = T \left(Z_{n+1} \left[1 + \cot \beta \tan i_1 \right] - H_1 \left[1 + \cot \beta \tan i_1 \right] - H_2 \tan i_1 (\cot \beta + \cot i_2) - x \tan i_1 \right)$$

Table 3 summarizes these formulae.

CASE A.3.a.

Figure 22 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting, and the resulting water pressure distribution.

1. Conditions for the crack positions

(i) n th crack in the lower slope:-

$$\underline{0 < \left\{K_1 + K_2 + \text{----} K_n\right\} < H_2 \cot i_2}$$

(ii) (n+1) th crack in the bench:-

(a) $A \cot \beta + K_{n+1} < H_2 \cot i_2 + x$

i.e. $K_{n+1} < H_2 \cot i_2 = x - A \cot \beta$

(b) $A \cot \beta + K_{n+1} > H_2 \cot i_2$

i.e. $K_{n+1} > H_2 \cot i_2 - A \cot \beta$

i.e. $\underline{H_2 \cot i_2 - A \cot \beta < K_{n+1} < H_2 \cot i_2 + x - A \cot \beta}$

2. Conditions for the water table

Water table above bottom of (n+1) th crack:- $\underline{H_w > B}$

When $H_w > H_2$ put $H_w = H_2$

3. Weight of the wedge, W

$$W = \gamma\left\{OO''Q'Q - OQQ' - O''E''O - ODD'' + ODP_0 - S''P_2Q'\right\}$$

$$= \gamma\left\{H_2^2 \cot \beta - \frac{H_2^2}{2} \cot \beta - \frac{H_2^2}{2} \cot i_2 - \frac{A^2}{2} \cot^2 \beta \tan i_2 + \frac{A^2}{2} \cot \beta - (H_2 - B)^2 \cot \beta\right\}$$

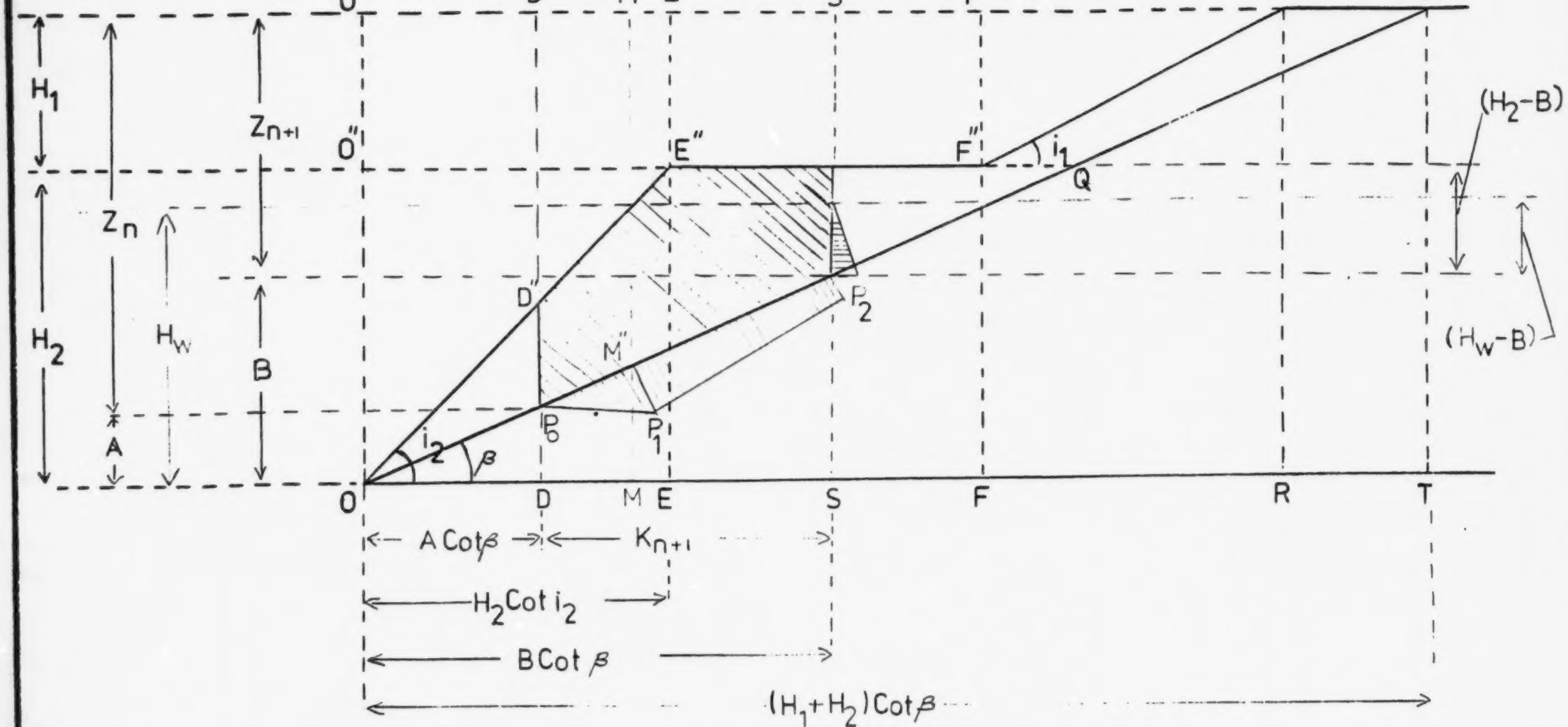
$$= \underline{\frac{\gamma}{2}\left\{H_2^2 (\cot \beta - \cot i_2) + A^2 \cot \beta (1 - \cot \beta \tan i_2) - (H_2 - B)^2 \cot \beta\right\}}$$

4. Pressures

$P_4 = 0$

$P_3 = 0$

$P_2 = \underline{\gamma_w \left\{H_w - B\right\} = \gamma_w \alpha}$


O'
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T'
H1
Zn
Zn+1
O''
E''
F''
i1
Q
(H2-B)
(Hw-B)
D''
M''
P2
P0
P1
H2
Hw
B
A
i2
β
O
D
M
E
S
F
R
T
A Cotβ
Kn+1
H2Cot i2
BCot β
(H1+H2)Cotβ

CASE A 3a

DWN. BY : K.B.
DATE :
SCALE : -
DWG. No. : FIG: 22

$$
\begin{aligned}
P_1 &= \gamma_w \left\{ H_2 - M''M - ME \tan i_2 \right\} \\
&= \gamma_w \left\{ H_2 - (A + DM \tan \beta) - ME \tan i_2 \right\} = \gamma_w \left\{ H_2 - A - \tan \beta \right. \\
&\quad \left. (DE - ME) - ME \tan i_2 \right\} \\
&= \gamma_w \left\{ H_2 - A - DE \tan \beta + ME (\tan \beta - \tan i_2) \right\} \\
&= \gamma_w \left\{ H_2 - A - (H_2 \cot i_2 - A \cot \beta) \tan \beta + (\tan \beta - \tan i_2)\ (H_2 - H_w) \right. \\
&\quad \left. \cot i_2 \right\} \\
&= \gamma_w \left\{ H_2 - A - H_2 \cot i_2 \tan \beta + A + (H_2 - H_w) \cot i_2 \tan \beta - (H_2 - H_w) \right\} \\
&= \underline{\gamma_w H_w (1 - \cot i_2 \tan \beta)}
\end{aligned}
$$

$$\underline{P_0 = 0}$$

5. Areas

$$\underline{A_T = \frac{1}{\sin \beta} \left\{ B - A \right\}}$$

$$\underline{A_1 = \frac{D M \tan \beta}{\sin \beta} = \frac{1}{\sin \beta} \left\{ M M'' - A \right\} = \frac{1}{\sin \beta} \left\{ H_w \cot i_2 \tan \beta - A \right\}}$$

$$\underline{A_2 = \frac{1}{\sin \beta} \left\{ P_2 S - M M'' \right\} = \frac{1}{\sin \beta} \left\{ B - H_w \cot i_2 \tan \beta \right\}}$$

A_3 - not required

A_4 - not required

6. Uplift Force, U

$$\underline{U = \tfrac{1}{2} \left\{ (P_3 + P_4)A_4 + (P_3 + P_2)A_3 + (P_2 + P_1)A_2 + (P_1 + P_0)A_1 \right\}}$$

7. Horizontal Force, V, due to water in the tension crack

$$V = \frac{P_2}{2} \left\{ H_w - B \right\} = \frac{P_2}{2} \alpha = \frac{\gamma_w}{2} \alpha^2$$

8. Resisting Force, Y, due to tensile strength across the potential crack

$$Y = T (Z_{n+1} - H_1) \quad \text{or} \quad T (H_2 - B)$$

Table 3 summarizes these formulae.

CASE A.3.b.

Figure 23 illustrates this case, gives some of the relevant dimensions, the position of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(i) n th crack in the lower slope:-

$$0 < \left(K_1 + K_2 + \text{----} K_n\right) < H_2 \cot i_2$$

(ii) (n+1) th crack in the bench:-

$$H_2 \cot i_2 - A \cot \beta < K_{n+1} < H_2 \cot i_2 + x - A \cot \beta$$

2. Conditions for the water table

(a) Below bottom of (n+1) th crack:- $H_w < B$

(b) Above n th crack top:- $H_w > DD''$ i.e. $H_w > A \cot \beta \tan i_2$

(c) When $H_w > H_2$ put $H_w = H_2$

3. Weight of the wedge, W

This is the same as case A.3.a. and is given by:-

$$W = \frac{\gamma}{2} \left(H_2^2(\cot \beta - \cot i_2) + A^2 \cot \beta \,(1 - \cot \beta \tan i_2) - (H_2 - B)^2 \cot \beta\right)$$

4. Pressures

$P_4 = 0$

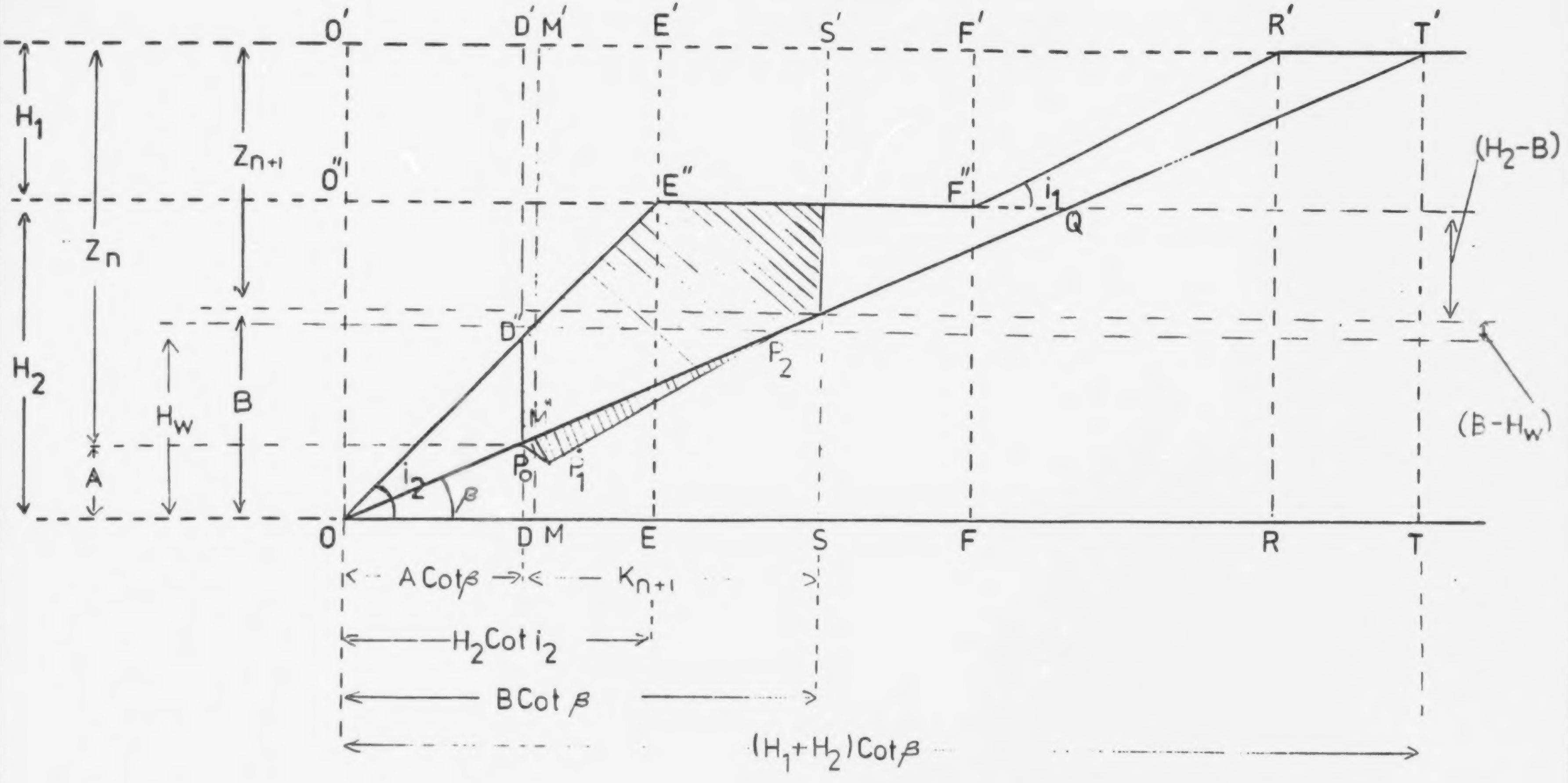
$P_3 = 0$

$P_2 = 0$

$$P_1 = \gamma_w \left(H_w - MM''\right) = \left(\gamma_w \quad H_w - H_w \cot i_2 \tan \beta\right)$$

$$= \gamma_w H_w \left(1 - \cot i_2 \tan \beta\right)$$

$P_0 = 0$


O'
D'
M'
E'
S'
F'
R'
T'
O''
E''
F''
i1
Q
(H2-B)
H1
Zn+1
Zn
H2
B
Hw
A
D''
M''
P0
P1
P2
i2
β
(B-Hw)
O
D
M
E
S
F
R
T
A Cotβ
Kn+1
H2Cot i2
BCot β
(H1+H2)Cotβ

CASE A 3b

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG: 23

5. Areas

$$\underline{A_T = \frac{1}{\sin\beta}\left(B - A\right)}$$

$$\underline{A_1 = \frac{1}{\sin\beta}\left(DM\tan\beta\right) = \frac{1}{\sin\beta}\left(MM'' - A\right) = \frac{1}{\sin\beta}\left(B\cot i_2\tan\beta - A\right)}$$

$$\underline{A_2 = \frac{1}{\sin\beta}\left(P_2L - MM''\right) = \frac{1}{\sin\beta}\left(H_w - B\cot i_2\tan\beta\right)}$$

A_3 - not required

A_4 - not required

6. Uplift Force, U

$$\underline{U = \tfrac{1}{2}\left((P_4 + P_3)A_4 + (P_3 + P_2)A_3 + (P_2 + P_1)A_2 + (P_1 + P_0)A_1\right)}$$

7. Horizontal Force, V, due to water in tension crack

$$\underline{V = 0}$$

8. Resisting Force, Y, due to tensile strength across the potential crack

$$\underline{Y = T\,(Z_{n+1} - H_1)}$$

Table 3 summarizes these formulae.

CASE A.3.c.

Figure 24 illustrates this case, gives some of the relevant dimensions, the position of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(i) n th crack in the lower slope:-

$$0 < \left\{K_1 + K_2 + ---- K_n\right\} < H_2 \cot i_2$$

(ii) (n+1) th crack in the bench:-

$$H_2 \cot i_2 - A \cot \beta < K_{n+1} < H_2 \cot i_2 + x - A \cot \beta$$

2. Conditions for the water table

Below top of n th creek:- $H_w < A \cot \beta \tan i_2$

When $H_w > H_2$ put $H_w = H_2$

3. Weight of wedge, W

This is the same as case A.3.a. and is given by:-

$$W = \frac{\gamma}{2} \left\{H_2^2 (\cot \beta - \cot i_2) + A^2 \cot \beta (1 - \cot \beta \tan i_2) - (H_2 - B)^2 \cot \beta\right\}$$

4. Pressures

$P_0 = P_1 = P_2 = P_3 = P_4 = 0$

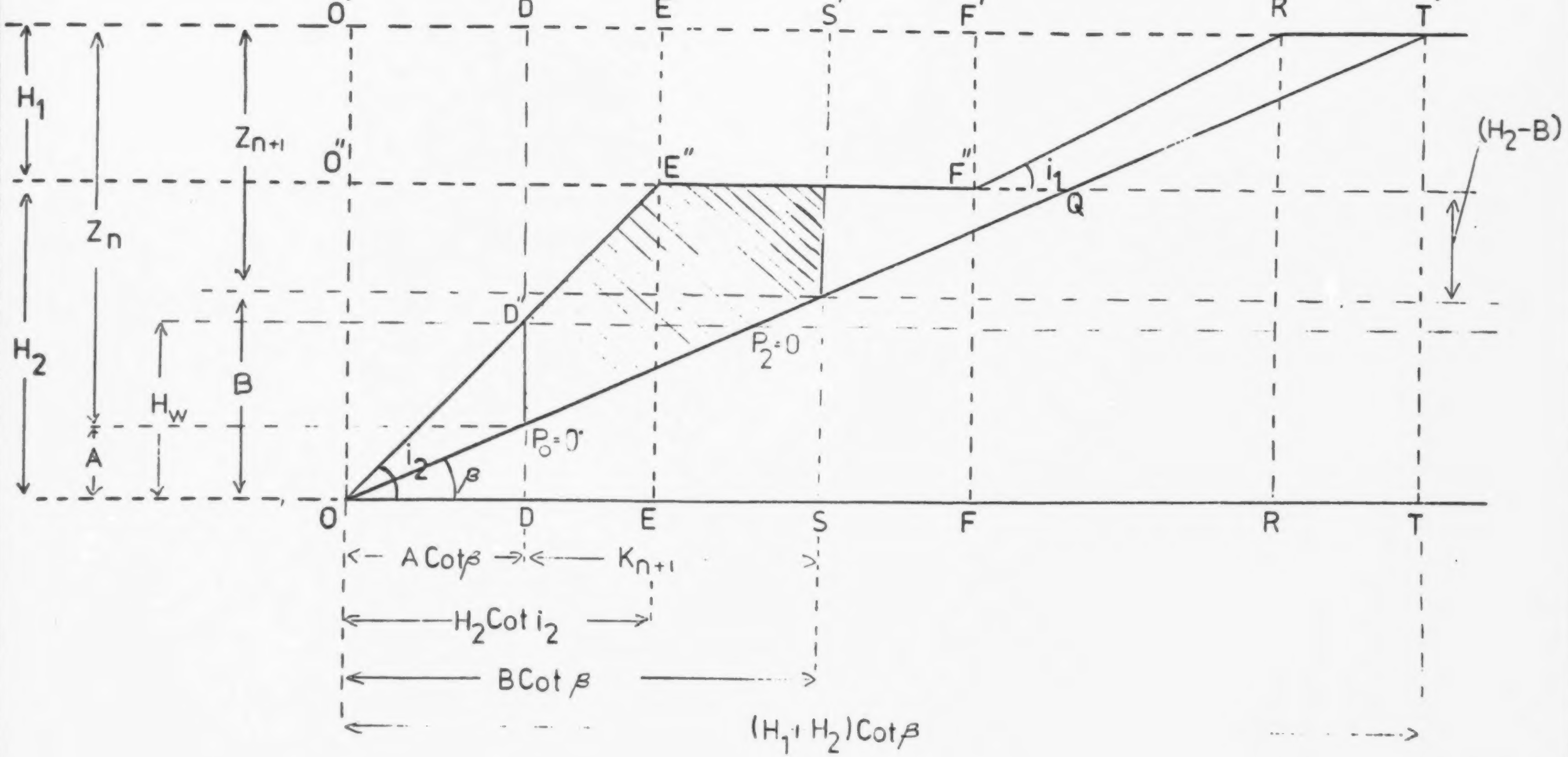
5. Areas

$$A_T = \frac{1}{\sin \beta} \left(B - A\right)$$

A_1, A_2, A_3 and A_4 not required.

6. Uplift Force, U

U = 0 since all pressures are zero


O'
D'
E'
S'
F'
R'
T'
H1
Zn+1
O"
E"
F"
i1
Q
(H2-B)
Zn
H2
D'
B
Hw
P2=0
A
i2
β
P0=0
O
D
E
S
F
R
T
A Cotβ
Kn+1
H2Cot i2
BCot β
(H1+H2)Cotβ

CASE A 3 c

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG: 24

7. Horizontal Force, V, due to water in the tension crack

   $V = 0$

8. Resisting Force, Y, due to tensile stress across the potential crack

   $Y = T\,(Z_{n+1} - H_1)$

Table 3 summarizes these formulae.

CASE A. 4.a.

Figure 25 illustrates this case, gives some of the relevant dimensions, the position of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(i) n th crack in the lower slope:-

$$\underline{0 < \left\{K_1 + K_2 \text{----} K_n\right\} < H_2 \cot i_2}$$

(ii) (n+1) th crack in the lower slope:-

$$\underline{0 < K_{n+1} < H_2 \cot i_2 - A \cot \beta}$$

2. Conditions for the water table

Water table above bottom of (n+1) th crack:- $\underline{H_W > B}$

When $H_W > B \cot_\beta \tan i_Z$
put $H_W = B \text{ Cot } \beta \tan i_Z$

3. Weight of the wedge, W

$$W = \gamma\left\{OS''S - OSP_2 - ODD'' + ODP_0\right\}$$

$$= \frac{\gamma}{2}\left\{B^2 \cot^2 \beta \tan i_2 - B^2 \cot \beta - A^2 \cot^2 \beta \tan i_2 + A^2 \cot \beta\right\}$$

$$= \underline{\frac{\gamma}{2} \cot \beta \left\{(\cot \beta \tan i_2 - 1)(B^2 - A^2)\right\}}$$

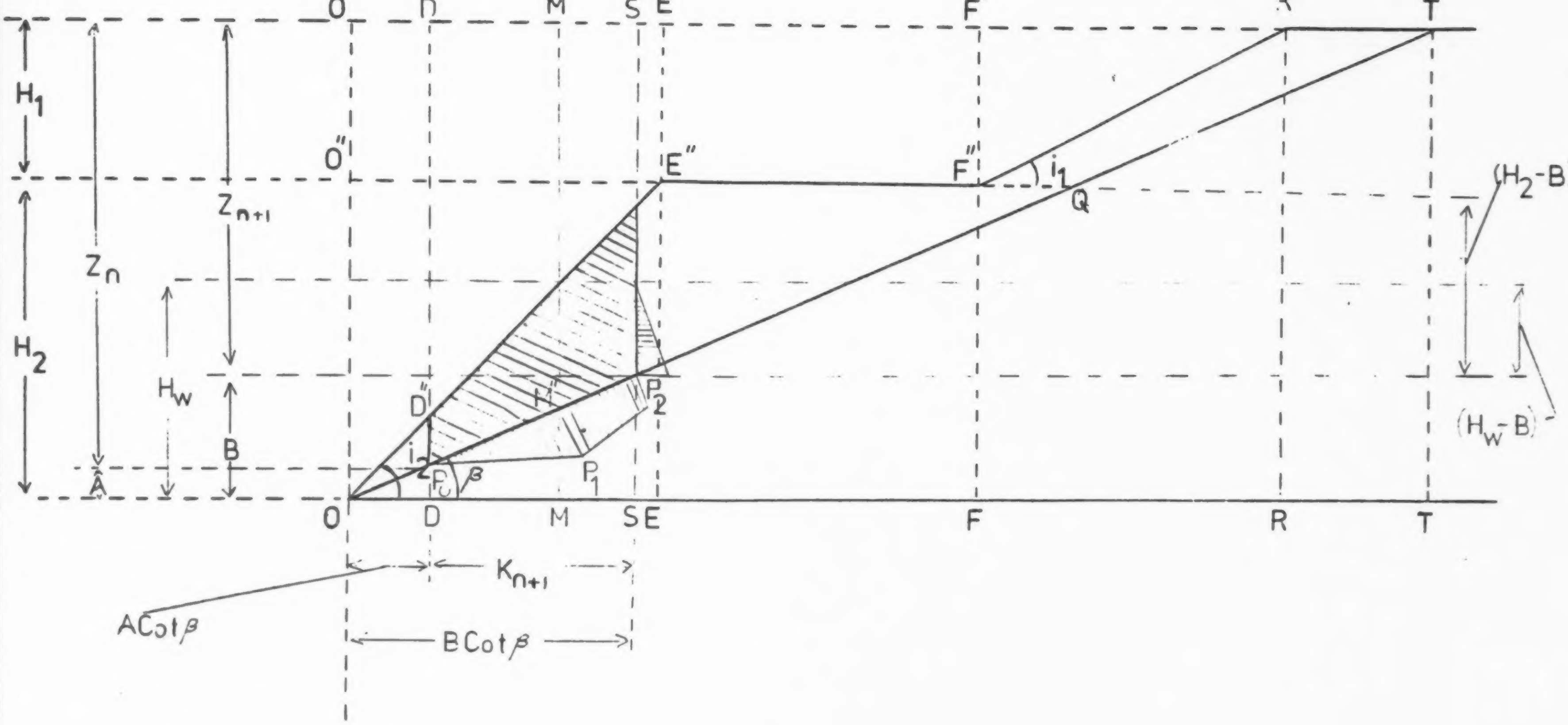
4. Pressures

$$P_0 = 0$$

$$P_1 = \gamma_W\left\{H_W - MM''\right\} = \gamma_W\left\{H_W - (A + DM \tan \beta)\right\}$$

$$= \gamma_W\left\{H_W - A - \tan \beta\,(DE - ME)\right\} = \gamma_W\left\{H_W - A - \tan \beta\left[H_2 \cot i_2 - A \cot \beta - (H_2 - H_W)\cot i_2\right]\right\}$$

$$= \gamma_W H_W (1 - \cot i_2 \tan \beta)$$


O'
D'
M'
S'
E'
F'
R'
T'
H1
H2
Zn
Zn+1
Hw
B
A
O''
E''
F''
i1
Q
(H2-B)
(Hw-B)
D''
M''
P2
P1
i2
P0
β
O
D
M
S
E
F
R
T
Kn+1
ACotβ
BCotβ

CASE A 4a

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG: 25

$$P_2 = \gamma_w (H_w - B)$$

$$P_3 = 0$$

$$P_4 = 0$$

5. Areas

$$A_T = \frac{1}{\sin \beta} \left(B - A\right)$$

$$A_1 = \frac{1}{\sin \beta} \left(D\,M \tan \beta\right) = \frac{1}{\sin \beta} \left(\tan \beta \;(D\,E - M\,E)\right) = \frac{1}{\sin \beta} \left(\tan \beta \;(H_2 \cot i_2 - A \cot \beta - (H_2 - H_w) \cot i_2)\right)$$

$$= \frac{1}{\sin \beta} \left(- A + H_w \cot i_2 \tan \beta\right) = \frac{1}{\sin \beta} \left(H_w \cot i_2 \tan \beta - A\right)$$

$$A_2 = \frac{1}{\sin \beta} \left(P_2S - M\,M''\right) = \frac{1}{\sin \beta} \left(B - (A + D\,M \tan \beta)\right)$$

$$= \frac{1}{\sin \beta} \left(B - A - \tan \beta \;(H_2 \cot i_2 - A \cot \beta - (H_2 - H_w) \cot i_2)\right)$$

$$= \frac{1}{\sin \beta} \left(B - H_w \cot i_2 \tan \beta\right)$$

A_3 and A_4 are not required.

6. Uplift Force, U

$$U = \tfrac{1}{2} \left((P_4 + P_3)A_4 + (P_3 + P_2)A_3 + (P_2 + P_1)A_2 + (P_1 + P_0)A_1\right)$$

7. Horizontal Force, V, due to water in the crack

$$V = \frac{P_2}{2} (H_w - B) = \frac{\gamma_w}{2} (H_w - B)^2 = \gamma_w\, \alpha^2/2$$

8. Resisting Force, Y, due to tensile strength across the potential crack

$$Y = T\left\{ Z_{n+1} - H_1 - (H_2 \cot i_2 - B \cot \beta) \tan i_2 \right\}$$

$$= T\left\{ Z_{n+1} - H_1 - H_2 + B \cot \beta \tan i_2 \right\}$$

Table 3 summarizes these formulae.

CASE A.4.b.

Figure 26 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(a) n th crack in the lower slope:-

$$0 < \left(K_1 + K_2 + \text{----} K_n\right) < H_2 \cot i_2$$

(b) (n+1) th crack in the lower slope:-

$$0 < K_{n+1} < H_2 \cot i_2 - A \cot \beta$$

2. Conditions for the water table

(a) water table below bottom of (n+1) th crack:- $H_w < B$

(b) above top of n th crack:- $H_w > A \cot \beta \tan i_2$

(c) When $H_w > B \cot\beta \tan i_Z$

put $H_w = B \text{ Cot } \beta \tan i_Z$

3. Weight of the wedge, W

This is the same as case A.4.a. and is given by:-

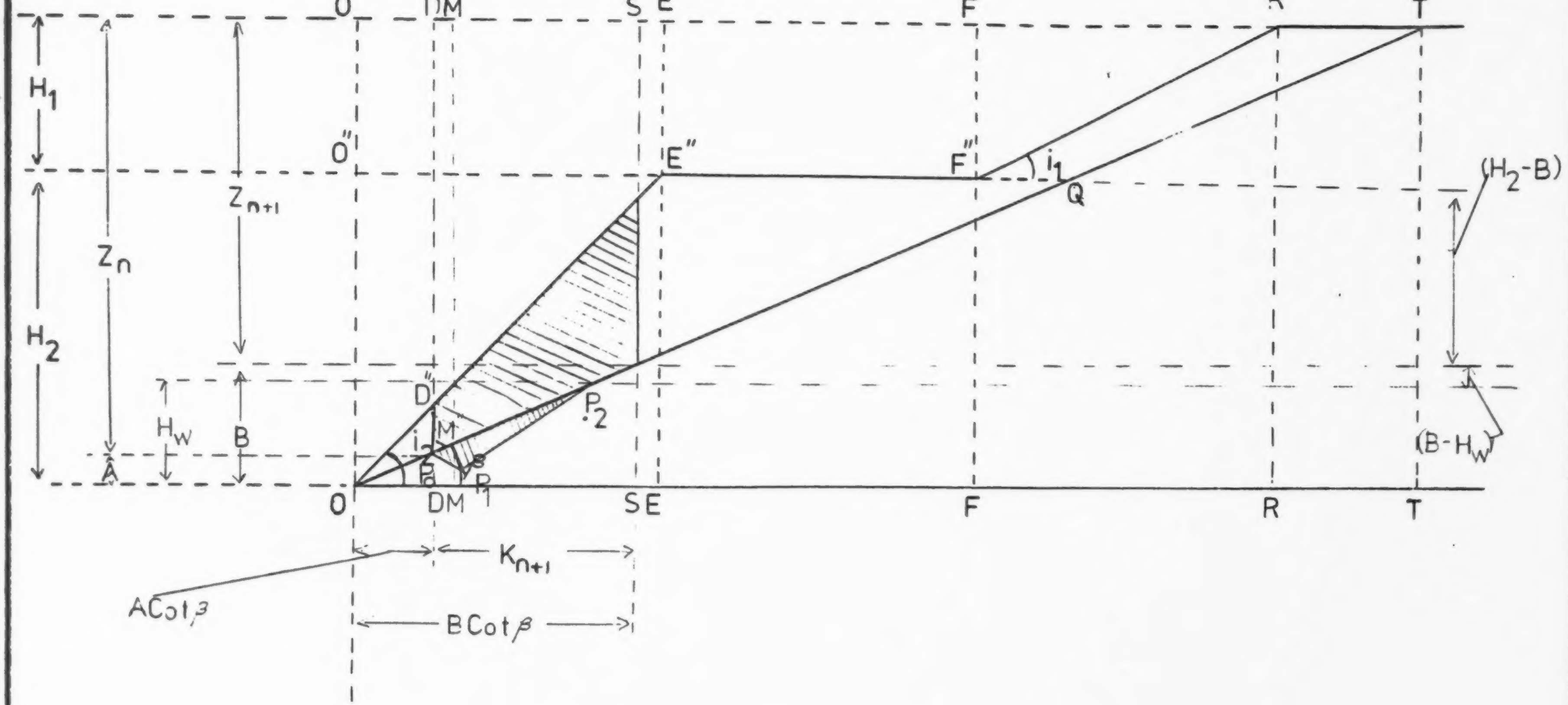
$$W = \frac{\gamma}{2} \cot \beta \left((\cot \beta \tan i_2 - 1) (B^2 - A^2)\right)$$

4. Pressures

$$P_0 = P_2 = P_3 = P_4 = 0$$

$$P_1 = \gamma_w \left(H_w - MM'\right) = \gamma_w \left(H_w - (A + DM \tan \beta)\right)$$

$$= \gamma_w \left(H_w - A - \tan \beta (DE - ME)\right) = \gamma_w \left(H_w - A - \tan \beta\right.$$
$$\left.(H_2 \cot i_2 - A \cot \beta - (H_2 - H_w) \cot i_2)\right)$$


O'
DM'
S'
E'
F'
R'
T'
H1
Zn
Z n+1
O''
E''
F''
i1
Q
(H2-B)
H2
D''
M
P2
Hw
B
A
i2
β
Pa
S
P1
(B-Hw)
O
DM
SE
F
R
T
K n+1
ACot β
BCot β

CASE A 4b

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG: 26

$$= \underline{\gamma_w H_w \left\{1 - \cot i_2 \tan \beta\right\}}$$

5. Areas

$$A_T = \frac{1}{\sin \beta} \left\{B - A\right\}$$

$$A_1 = \frac{1}{\sin \beta} (D M \tan \beta) = \frac{1}{\sin \beta} \left\{\tan \beta \, (D E - M E)\right\} = \frac{1}{\sin \beta} \left\{\tan \beta \, (H_2 \cot i_2 - A \cot \beta - (H_2 - H_w) \cot i_2\right\}$$

$$= \frac{1}{\sin \beta} \left\{- A + H_w \cot i_2 \tan \beta\right\} = \underline{\frac{1}{\sin \beta} \left\{H_w \cot i_2 \tan \beta - A\right\}}$$

$$A_2 = \frac{1}{\sin \beta} \left\{H_w - M M''\right\} = \underline{\frac{1}{\sin \beta} \left\{H_w (1 - \cot i_2 \tan \beta)\right\}}$$

A_3 and A_4 are not required.

6. Uplift Force, U

$$U = \tfrac{1}{2} \left\{(P_4 + P_3)A_4 + (P_3 + P_2)A_3 + (P_2 + P_1)A_2 + (P_1 + P_0)A_1\right\}$$

7. Horizontal Force, V, due to water in the tension crack

$V = 0$

8. Resisting Force, Y, due to tensile strength across the potential crack

$$\underline{Y = T \left\{Z_{n+1} - H_1 - H_2 + B \cot \beta \tan i_2\right\}}$$

Table 3 summarizes these formulae.

CASE A.4.c.

Figure 27 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

   (a) n th crack in the lower slope:-

   $$0 < \left(K_1 + K_2 ---- K_n\right) < H_2 \cot i_2$$

   (b) (n+1) th crack in the lower slope:-

   $$0 < K_{n+1} < H_2 \cot i_2 - A \cot \beta$$

2. Conditions for the water table

   Water table below top of the n th crack:- $H_w < A \cot \beta \tan i_2$

   When $H_w > B \cot \beta \tan i_Z$

   put $H_w = B \text{ Cot } \beta \tan i_Z$

3. Weight of the wedge, W

   This is the same as case A.4.a. and is given by:-

   $$W = \frac{\gamma}{2} \cot \beta \left((\cot \beta \tan i_2 - 1)(B^2 - A^2)\right)$$

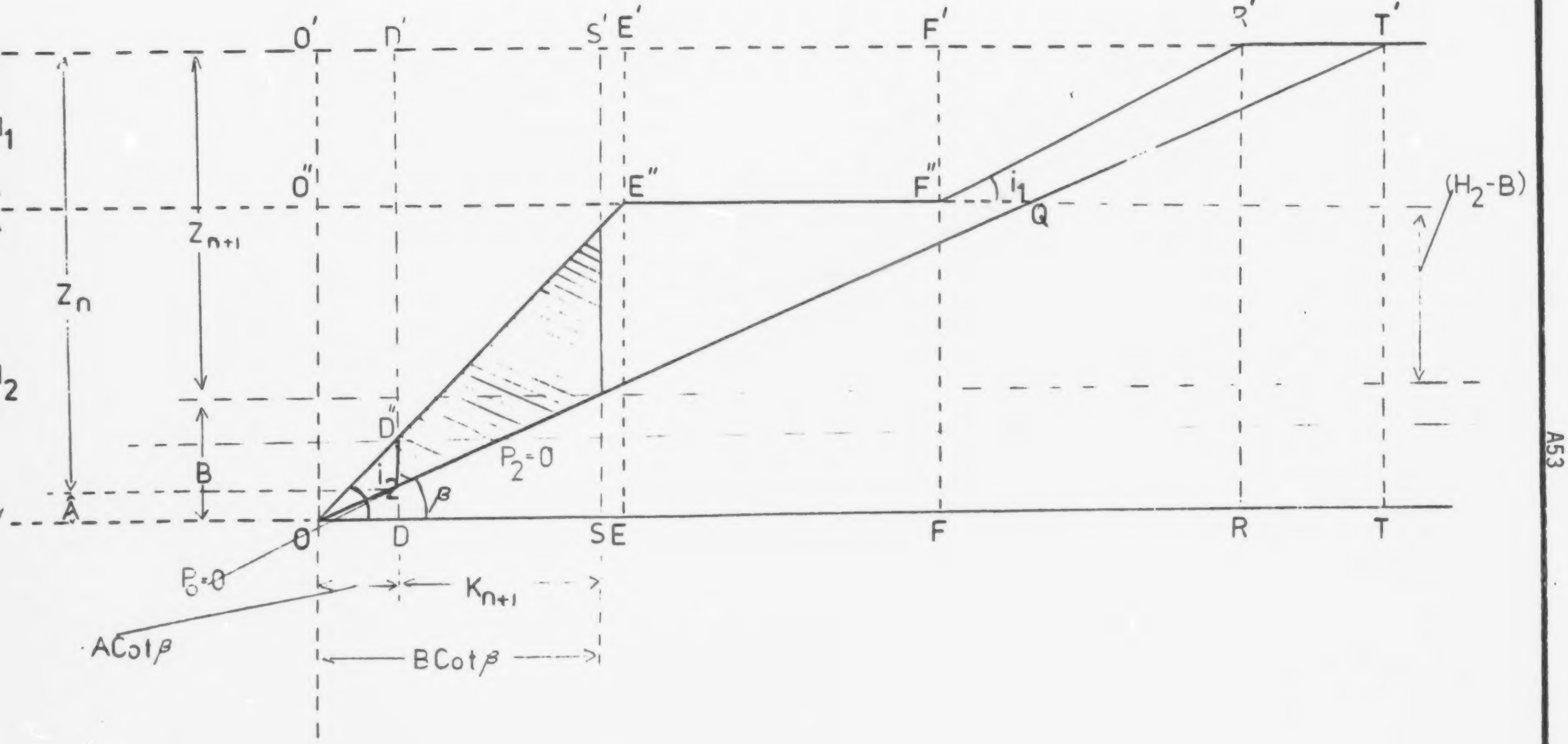
4. Pressures

   $$P_0 = P_1 = P_2 = P_3 = P_4 = 0$$

5. Areas

   $$A_T = \frac{1}{\sin \beta} \left(B - A\right)$$

   A_1, A_2, A_3 and A_4 are not required since all pressures are zero.


O'
D'
S'
E'
F'
R'
T'
O''
E''
F''
i_1
Q
(H_2-B)
Z_{n+1}
Z_n
B
A
D''
i_2
$P_2=0$
β
O
D
SE
F
R
T
$P_0=0$
K_{n+1}
ACotβ
BCotβ

CASE A 4c

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG: 27

6. Uplift Force, U

   $U = 0$

7. Horizontal Force, V, due to water in the tension crack

   $V = 0$

8. Resisting Force, Y, due to tensile strength across the potential crack

   $$Y = T \left(Z_{n+1} - H_1 - H_2 + B \cot \beta \tan i_2 \right)$$

Table 3 summarizes these formulae.

CASE B.1.a.

Figure 28 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(a) n th crack in the bench:-

$$\underline{H_2 \cot i_2 < \left(K_1 + K_2 --- K_n\right) < (H_2 \cot i_2 + x)}$$

(b) (n+1) th crack in the crest:-

$$A \cot \beta + K_{n+1} > H_2 \cot i_2 + x + H_1 \cot i_1$$

$$\underline{\text{i.e. } K_{n+1} > H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta}$$

and $\underline{K_{n+1} < (H_1 + H_2) \cot \beta - A \cot \beta}$

2. Conditions for the water table

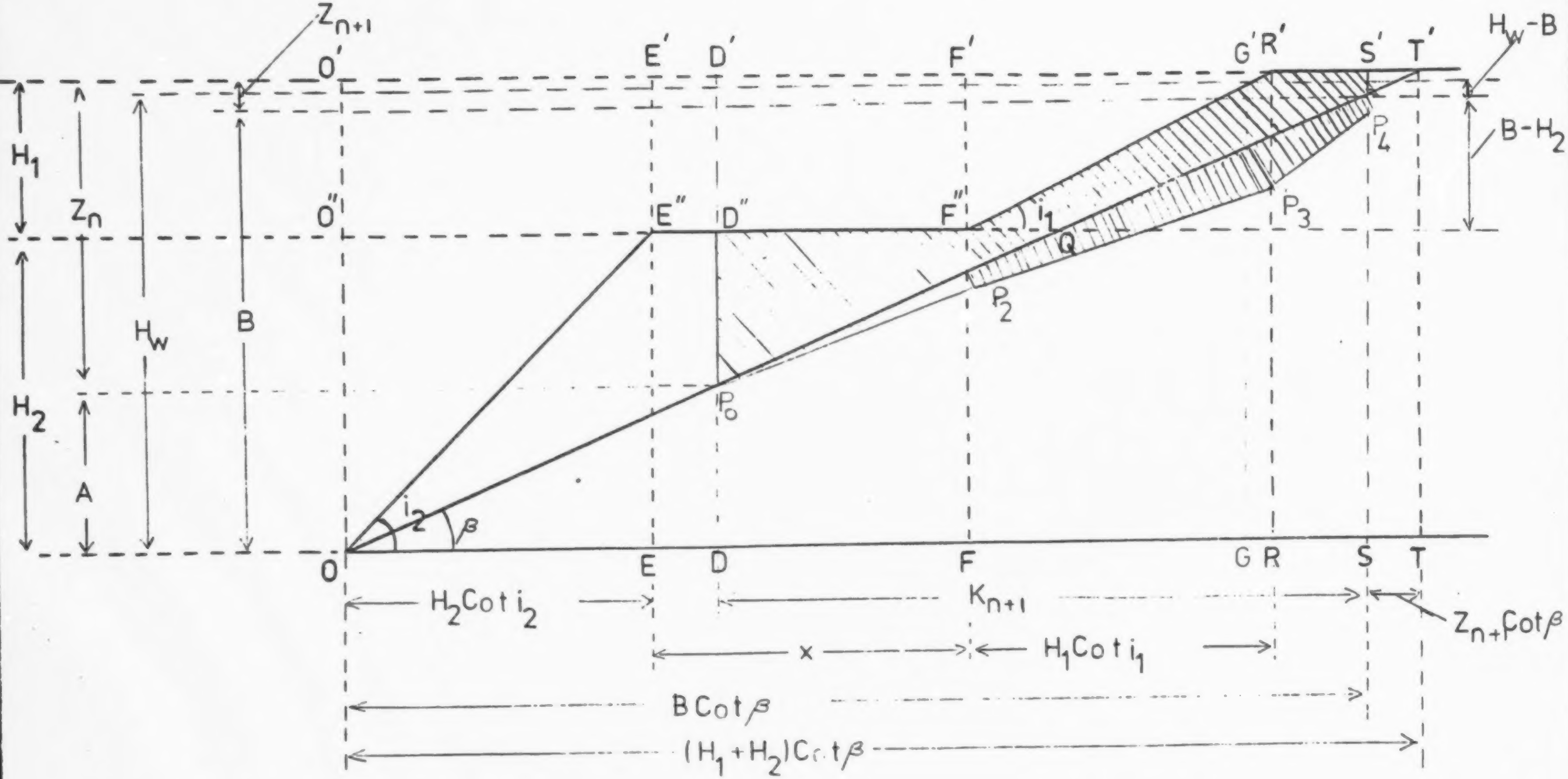
Water table above bottom of (n+1) th crack:- $\underline{H_w > B}$

3. Weight of the wedge, W

$$W = \gamma \left(D'P_0T' - D'D''F''F' - F''F'R' - S'P_4T'\right)$$

$$= \frac{\gamma}{2} \left(Z_n{}^2 \cot \beta - 2 H_1 (x - A \cot \beta + H_2 \cot i_2) - H_1{}^2 \cot i_1 - Z_{n+1}{}^2 \cot \beta\right)$$

$$= \underline{\frac{\gamma}{2} \left(\cot \beta (Z_n{}^2 - Z_{n+1}{}^2) + H_1 \left[2 A \cot \beta - 2 H_2 \cot i_2 - H_1 \cot i_1 - 2x\right]\right)}$$


Z_{n+1}
O'
E'
D'
F'
G'R'
S'
T'
H_w-B
B-H_2
H_1
Z_n
H_w
B
H_2
A
O''
E''
D''
F''
i_1
Q
P_2
P_3
P_4
P_0
i_2
β
O
E
D
F
G R
S
T
H_2Cot i_2
K_{n+1}
Z_{n+1}Cot β
x
H_1Cot i_1
B Cot β
(H_1+H_2)Cot β

CASE B1a

DWN. BY : K.B.
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SCALE : -
DWG. No. : FIG: 28

4. Pressures

$\underline{P_0 = 0 \quad P_1 \text{ not required, } = 0}$

$$P_2 = \gamma_w \left\{ F''P_2 \right\} = \gamma_w \left\{ H_2 - P_2F \right\} = \gamma_w \left\{ H_2 - \left[H_2 \cot i_2 + x \right] \tan \beta \right\}$$

$$= \underline{\gamma_w \left\{ H_2 (1 - \cot i_2 \tan \beta) - x \tan \beta \right\}}$$

$$P_3 = \gamma_w \left\{ H_w - P_3G \right\} = \gamma_w \left\{ H_w - \tan \beta \, (H_2 \cot i_2 + x + H_1 \cot i_1 - GR) \right\}$$

$$= \gamma_w \left\{ H_w - \tan \beta \left[H_2 \cot i_2 + x + H_1 \cot i_1 - (H_1 + H_2 - H_w) \cot i_1 \right] \right\}$$

$$= \underline{\gamma_w \left\{ H_w (1 - \cot i_1 \tan \beta) + \tan \beta \left[H_2 (\cot i_1 - \cot i_2) - x \right] \right\}}$$

$$\underline{P_4 = \gamma_w (H_w - B) = \gamma_w \alpha}$$

5. Areas

$$A_T = \frac{1}{\sin \beta} \left\{ B - A \right\}$$

$$A_1 + A_2 = \frac{1}{\sin\beta}\, D\,F \tan\beta = \frac{1}{\sin\beta}\left(\tan\beta\,(H_2 \cot i_2 + x - A \cot\beta)\right)$$

$$\underline{= \frac{1}{\sin\beta}\left(H_2 \cot i_2 \tan\beta + x \tan\beta - A\right)}$$

$$A_3 = \frac{1}{\sin\beta}\, F\,G \tan\beta = \frac{1}{\sin\beta}\left(\tan\beta\,(F\,R - G\,R)\right)$$

$$= \frac{1}{\sin\beta}\left(\tan\beta\,(H_1 \cot i_1 - (H_1 + H_2 - H_w) \cot i_1)\right)$$

$$\underline{= \frac{1}{\sin\beta}\left(\cot i_1 \tan\beta\,(H_w - H_2)\right)}$$

$$A_4 = \frac{1}{\sin\beta}\, R\,S \tan\beta = \frac{1}{\sin\beta}\left(\tan\beta\left[(H_1 + H_2) \cot\beta - Z_{n+1} \cot\beta - H_1 \cot i_1 - x - H_2 \cot i_2\right]\right)$$

$$= \frac{1}{\sin\beta}\left(H_1 + H_2 - Z_{n+1} - H_1 \cot i_1 \tan\beta - x \tan\beta - H_2 \cot i_2 \tan\beta\right)$$

$$\underline{= \frac{1}{\sin\beta}\left(B - \tan\beta\left[H_1 \cot i_1 + x + H_2 \cot i_2\right]\right)}$$

6. **Uplift Force, U**

$$\underline{U = \tfrac{1}{2}\left((A_1 + A_2)(P_0 + P_2) + A_3\,(P_2 + P_3) + A_4(P_3 + P_4)\right)}$$

7. Horizontal Force, V, due to water in the tension crack

$$V = \frac{P_4}{2} (H_w - B) = \gamma_w \alpha^2/_2$$

8. Resisting Force, Y, due to tensile strength across the potential crack

$$Y = T Z_{n+1}$$

Table 4 summarizes these formulae.

CASE B.1.b.

Figure 29 illustrates this case, gives some of the relevant dimensions, the position of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(a) n th crack in the bench:-

$$\underline{H_2 \cot i_2 < \left(K_1 + K_2 \text{----} K_n\right) < (H_2 \cot i_2 + x)}$$

(b) (n+1) th crack in the crest:-

$$\underline{K_{n+1} > H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta}$$

and $K_{n+1} < (H_1 + H_2) \cot \beta - A \cot \beta$

2. Conditions for the water table

(a) Below the bottom of the (n+1) th creek $\underline{H_W < B}$

(b) Above H_2 $\underline{H_W > H_2}$

3. Weight of the wedge, W

This is the same as case B.1.a. and is given by:-

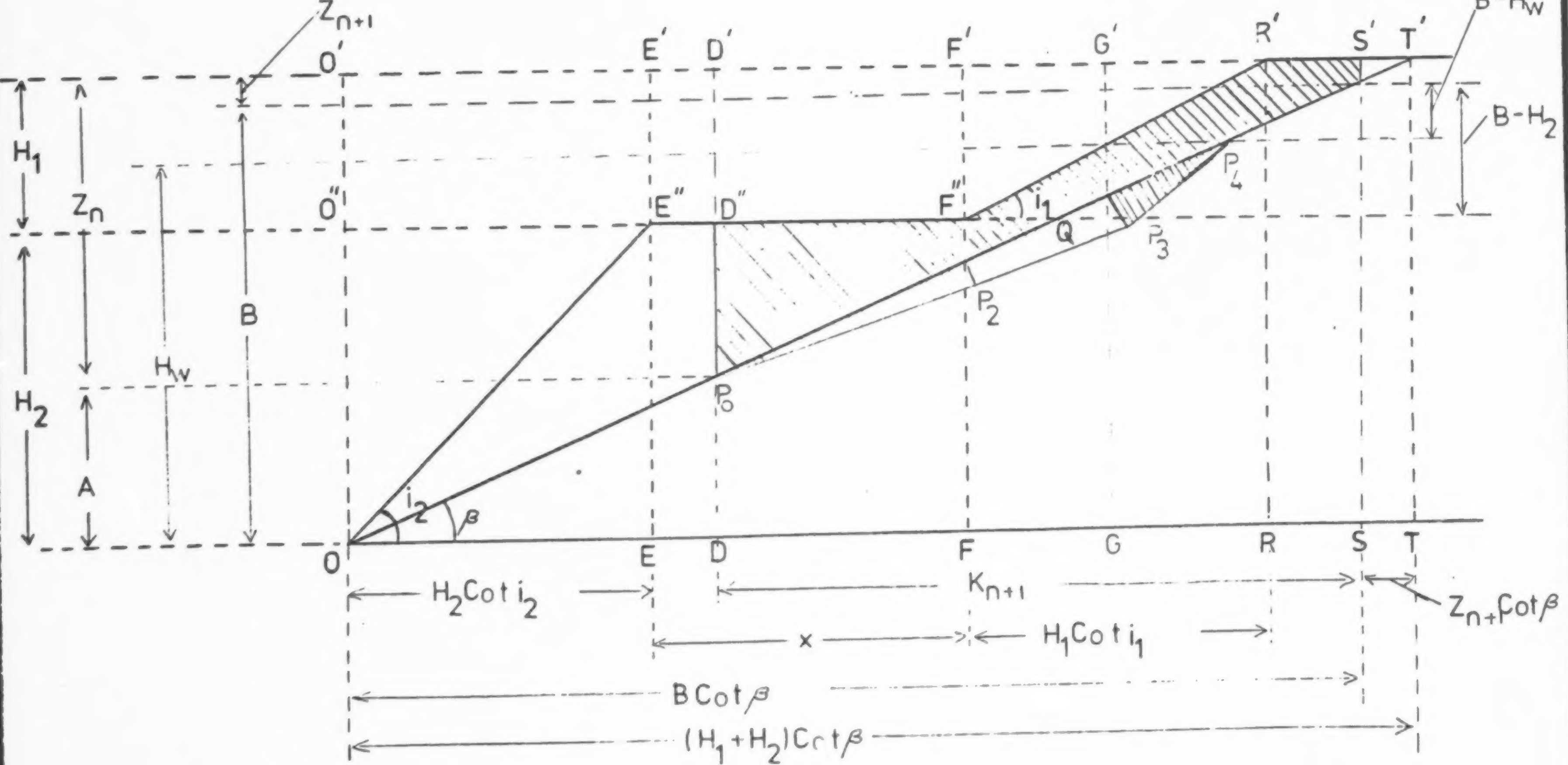
$$\underline{W = \frac{\gamma}{2} \left(\cot \beta (Z_n{}^2 - Z_{n+1}{}^2) + H_1 \left[2 A \cot \beta - 2 H_2 \cot i_2 - H_1 \cot i_1 - 2x\right]\right)}$$

4. Pressures

$P_0 = P_4 = 0$ P_1 not required.

$P_2 = \gamma_W \left(H_2 - P_2F\right)$

$$= \underline{\gamma_W \left(H_2 (1 - \cot i_2 \tan \beta) - x \tan \beta\right)}$$


Z_{n+1}
O'
E'
D'
F'
G'
R'
S'
T'
B-H_W
B-H_2
H_1
Z_n
H_w
B
O''
E''
D''
F''
i_1
Q
P_2
P_3
P_4
P_0
H_2
A
i_2
β
O
E
D
F
G
R
S
T
H_2Cot i_2
K_{n+1}
Z_{n+1}Cot β
x
H_1Cot i_1
BCot β
(H_1+H_2)Cot β

CASE B1b

DWN. BY : K.B.
DATE :
SCALE : -
DWG. No. : FIG: 29

$$P_3 = \gamma_w \left\{ H_w - P_3 G \right\}$$

$$= \gamma_w \left\{ H_w - \tan\beta \,(H_2 \cot i_2 + x + H_1 \cot i_1 - G R) \right\}$$

$$= \gamma_w \left\{ H_w - \tan\beta \,(H_2 \cot i_2 + x + H_1 \cot i_1 - (H_1 + H_2 - H_w) \cot i_1) \right\}$$

$$= \underline{\gamma_w \left\{ H_w (1 - \cot i_1 \tan\beta) + \tan\beta \left[H_2 (\cot i_1 - \cot i_2) - x \right] \right\}}$$

5. Areas

$$\underline{A_T = \frac{1}{\sin\beta} \left\{ B - A \right\}}$$

$$A_1 + A_2 = \frac{1}{\sin\beta} \left\{ D F \tan\beta \right\} = \frac{1}{\sin\beta} \left\{ \tan\beta \left[H_2 \cot i_2 + x - A \cot\beta \right] \right\}$$

$$= \underline{\frac{1}{\sin\beta} \left\{ H_2 \cot i_2 \tan\beta + x \tan\beta - A \right\}}$$

$$A_3 = \frac{1}{\sin\beta} F G \tan\beta = \frac{1}{\sin\beta} \left\{ \tan\beta \,(F R - G R) \right\}$$

$$= \frac{1}{\sin\beta} \left\{ \tan\beta \left[H_1 \cot i_1 - (H_1 + H_2 - H_w) \cot i_1 \right] \right\}$$

$$= \underline{\frac{1}{\sin\beta} \left\{ \cot i_1 \tan\beta \,(H_w - H_2) \right\}}$$

$$A_4 = \frac{1}{\sin\beta}\left(G'L' \tan\beta\right)$$ which is same as A.2.b.

$$= \frac{1}{\sin\beta}\left(\tan\beta \;\; H_2\,(\cot i_1 - \cot i_2) - H_w \cot i_i - x \quad + H_w\right)$$

6. Uplift Force, U

$$U = \tfrac{1}{2}\left((A_1 + A_2)(P_0 + P_2) + A_3\,(P_2 + P_3) + A_4\,(P_3 + P_4)\right)$$

7. Horizontal Force, V, due to water in the tension crack

$V = 0$

8. Resisting Force, Y, due to tensile strength across the potential crack

$Y = T \;\; Z_{n+1}$

Table 4 summarizes these formulae.

CASE B.1.c.

Figure 30 illustrates this case, gives some of the relevant dimensions, the position of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(a) n th crack in the bench:-

$$H_2 \cot i_2 < \left(K_1 + K_2 + \text{----} K_n\right) < (H_2 \cot i_2 + x)$$

(b) (n+1) th crack in the crest:-

$$K_{n+1} > H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$$

and $K_{n+1} < (H_1 + H_2) \cot \beta - A \cot \beta$

2. Conditions for the water table

Water table below H_2:- $H_w < H_2$

3. Weight of the wedge, W

This is the same as case B.1.a. and is given by:-

$$W = \frac{\gamma}{2} \left\{\cot \beta (Z_n^{\,2} - Z_{n+1}^{\,2}) + H_1 \left[2 A \cot \beta - 2 H_2 \cot i_2 - H_1 \cot i_1 - 2x\right]\right\}$$

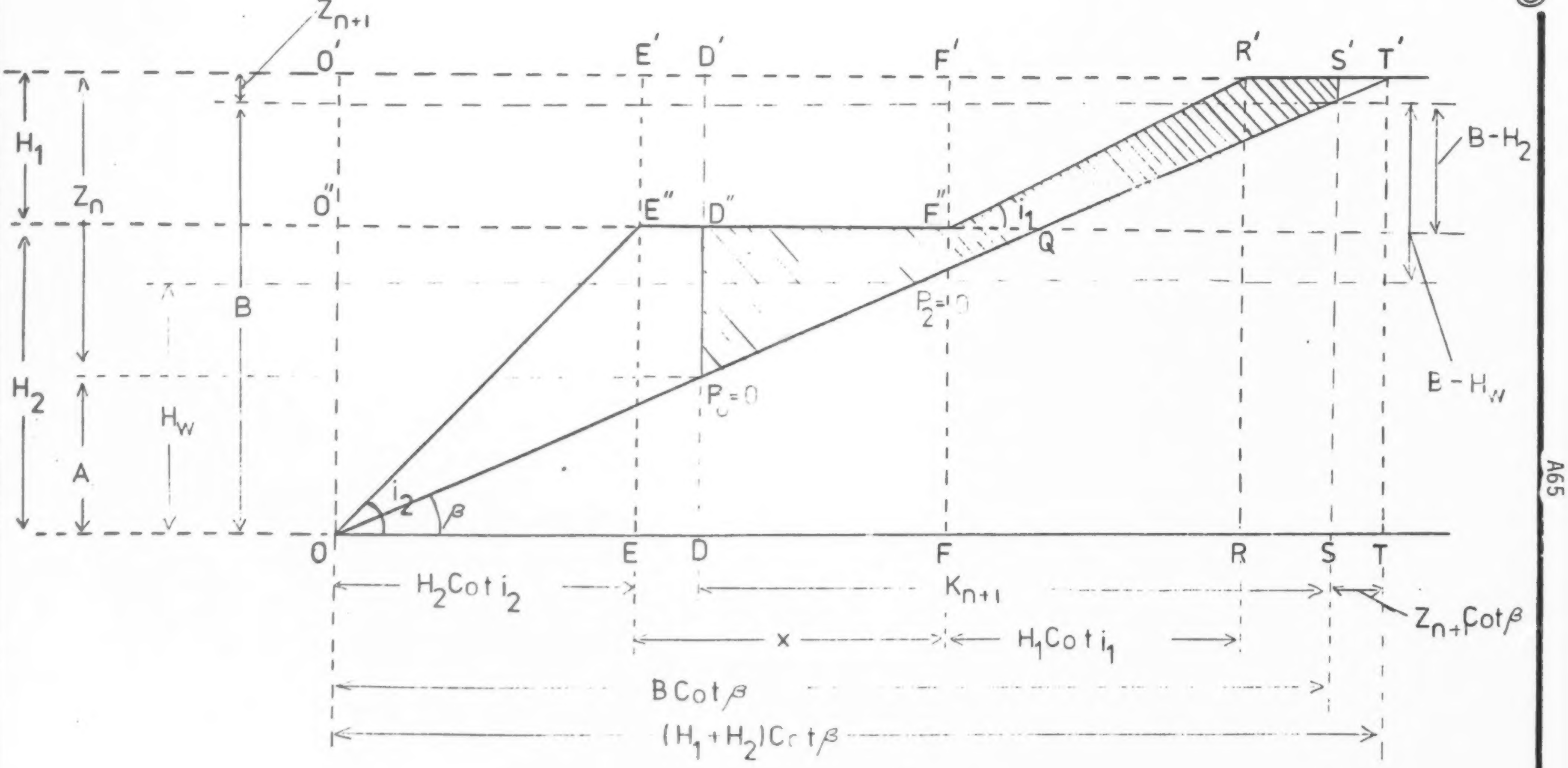
4. Pressures

$$P_0 = P_1 = P_2 = P_3 = P_4 = 0$$

5. Areas

$$A_T = \frac{1}{\sin \beta} \left(B - A\right)$$

A_1, A_2, A_3 and A_4 not required since all pressures are zero.


Z_{n+1}
O'
E'
D'
F'
R'
S'
T'
H_1
Z_n
O''
E''
D''
F''
i_1
Q
B
B-H_2
P_2=0
H_2
H_W
P_0=0
B-H_W
A
i_2
β
O
E
D
F
R
S
T
H_2 Cot i_2
K_{n+1}
Z_{n+1} Cot β
x
H_1 Cot i_1
B Cot β
(H_1+H_2) Cot β

CASE B1c

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG: 30

6. Uplift Force, U

   $U = 0$

7. Horizontal Force, V, due to water in the crack

   $V = 0$

8. Resisting Force, Y, due to tensile strength across the potential crack

   $Y = T\ Z_{n+1}$

Table 4 summarizes these formulae.

CASE B.2.a.

Figure 31 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(a) n th crack in the bench:-

$$H_2 \cot i_2 < \left\{K_1 + K_2 \text{ --- } K_n\right\} < (H_2 \cot i_2 + x)$$

(b) (n+1) th crack in upper slope:-

$$A \cot \beta + K_{n+1} < H_2 \cot i_2 + x + H_1 \cot i_1$$

and $A \cot \beta + K_{n+1} > H_2 \cot i_2 + x$

i.e. $H_2 \cot i_2 + x - A \cot \beta < K_{n+1} < H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$

2. Conditions for the water table

Water table above bottom of (n+1) th crack:- $H_W > B$

When $H_w > H_2 (1 - \cot i_2 \tan i_1) + B \operatorname{Cot} \beta \tan i_1 - x \tan i_1$

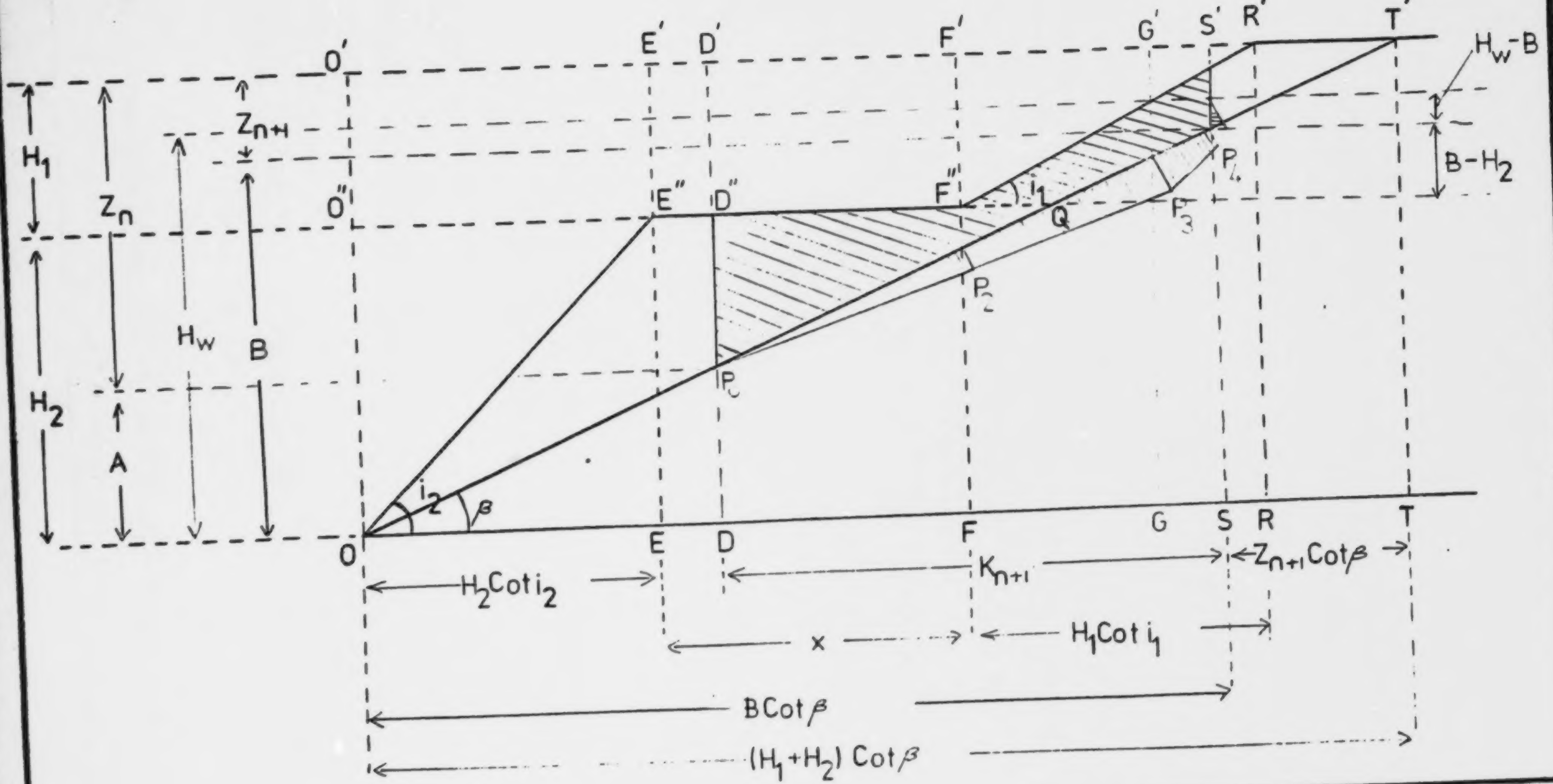
put $H_w = H_2 (1 - \operatorname{Cot} i_2 \tan i_1) + B \operatorname{Cot} \beta \tan i_1 - x \tan i_1$

3. Weight of the wedge, W

$$W = \gamma \left\{D'P_0T' - D''D'F'F'' - F''F'R' - S'P_4T' + S'S''R'\right\}$$

$$= \frac{\gamma}{2} \left\{Z_n^2 \cot \beta - 2 H_1 (x + H_2 \cot i_2 - A \cot \beta) - H_1^2 \cot i_1 - Z_{n+1}^2 \cot \beta + (H_2 \cot i_2 + x + H_1 \cot i_1 - B \cot \beta)^2 \tan \beta\right\}$$

$$= \frac{\gamma}{2} \left\{\cot \beta (Z_n^2 - Z_{n+1}^2) + H_1 (2 A \cot \beta - 2 H_2 \cot i_2 - H_1 \cot i_1 - 2x) + (H_2 \cot i_2 + x + H_1 \cot i_1 - B \cot \beta)^2 \tan \beta\right\}$$


O'
E'
D'
F'
G'
S'
R'
T'
H_w-B
B-H_2
H_1
Z_n
Z_{n+1}
H_w
B
H_2
A
O''
E''
D''
F''
i_1
Q
P_4
P_3
P_2
P_0
i_2
β
O
E
D
F
G
S
R
T
H_2Coti_2
K_{n+1}
Z_{n+1}Cotβ
x
H_1Coti_1
BCotβ
(H_1+H_2) Cotβ

CASE B2a

DWN. BY : K.B.

DATE :

SCALE : -

DWG. No. : FIG: 31

4. **Pressures**

$P_0 = 0$, P_1 not required.

$$P_2 = \gamma_w \left\{H_2 - P_2F\right\} = \gamma_w \left\{H_2 - (H_2 \cot i_2 + x) \tan \beta\right\}$$

$$= \underline{\gamma_w \left\{H_2 (1 - \cot i_2 \tan \beta) - x \tan \beta\right\}}$$

$$P_3 = \gamma_w \left\{H_w - P_3G\right\} = \gamma_w \left\{H_w - \tan \beta\, (H_2 \cot i_2 + x + H_1 \cot i_1 - G R)\right\}$$

$$= \gamma_w \left\{H_w - \tan \beta\, (H_2 \cot i_2 + x + H_1 \cot i_1 - (H_1 + H_2 - H_w) \cot i_1)\right\}$$

$$= \underline{\gamma_w \left\{H_w (1 - \cot i_1 \tan \beta) + \tan \beta \left[H_2 (\cot i_1 - \cot i_2) - x\right]\right\}}$$

$$\underline{P_4 = \gamma_w (H_w - B) = \alpha \gamma_w}$$

5. **Areas**

$$\underline{A_T = \frac{1}{\sin \beta} \left\{B - A\right\}}$$

$$(A_1 + A_2) = \frac{1}{\sin \beta} \left\{\tan \beta\, (H_2 \cot i_2 + x - A \cot \beta)\right\}$$

$$= \underline{\frac{1}{\sin \beta} \left\{H_2 \cot i_2 \tan \beta + x \tan \beta - A\right\}}$$

$$A_3 = \frac{1}{\sin \beta} F G \tan \beta = \frac{1}{\sin \beta} \left\{ \tan \beta \left(F R - G R \right) \right\}$$

$$= \frac{1}{\sin \beta} \left\{ \tan \beta \left[H_1 \cot i_1 - (H_1 + H_2 - H_w) \cot i_1 \right] \right\}$$

$$\underline{= \frac{1}{\sin \beta} \left\{ \cot i_1 \tan \beta \left(H_w - H_2 \right) \right\}}$$

$A_4 = \frac{1}{\sin \beta} \left\{ G'S' \tan \beta \right\}$ which is the same as case A.2.a.

$$\underline{= \frac{1}{\sin \beta} \left\{ B + \tan \beta \left[H_2 (\cot i_1 - \cot i_2) - H_w \cot i_1 - x \right] \right\}}$$

6. Uplift Force, U

$$\underline{U = \tfrac{1}{2} \left\{ (A_1 + A_2)(P_0 + P_2) + (A_3)(P_2 + P_3) + A_4 (P_3 + P_4) \right\}}$$

7. Horizontal Force, V, due to water in the tension crack

$$\underline{V = \frac{P_4}{2} (H_w - B) = \gamma_w \, \alpha^2/2}$$

8. Resisting Force, Y, due to tensile strength across the potential crack

$Y = T (Z_{n+1} - S'R' \tan i_1)$ which is the same as case A.2.a.

$$\underline{= T \left\{ Z_{n+1} \left[1 + \cot \beta \tan i_1 \right] - H_1 \left[1 + \cot \beta \tan i_1 \right] - H_2 \tan i_1 (\cot \beta + \cot i_2) - x \tan i_1 \right\}}$$

Table 4 summarizes these formulae.

CASE B.2.b.

Figure 32 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(a) n th crack in the bench:-

$$\underline{H_2 \cot i_2 < \left(K_1 + K_2 ---- K_n\right) < H_2 \cot i_2 + x}$$

(b) (n+1) th crack in upper slope:-

$$\underline{H_2 \cot i_2 + x - A \cot \beta < K_{n+1} < H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta}$$

2. Conditions for the water table

(a) Below bottom of (n+1) th crack $\underline{H_w < B}$

(b) Above H_2 $\underline{H_w > H_2}$

(c) When $H_w > H_2 (1 - \cot i_2 \tan i_1) + B \text{ Cot } \beta \tan i_1 - x \tan i_1$

put $H_w = H_2 (1 - \text{Cot } i_2 \tan i_1) + B \text{ Cot } \beta \tan i_1 - x \tan i_1$

3. Weight of the wedge, W

This is the same as case B.2.a. and is given by:-

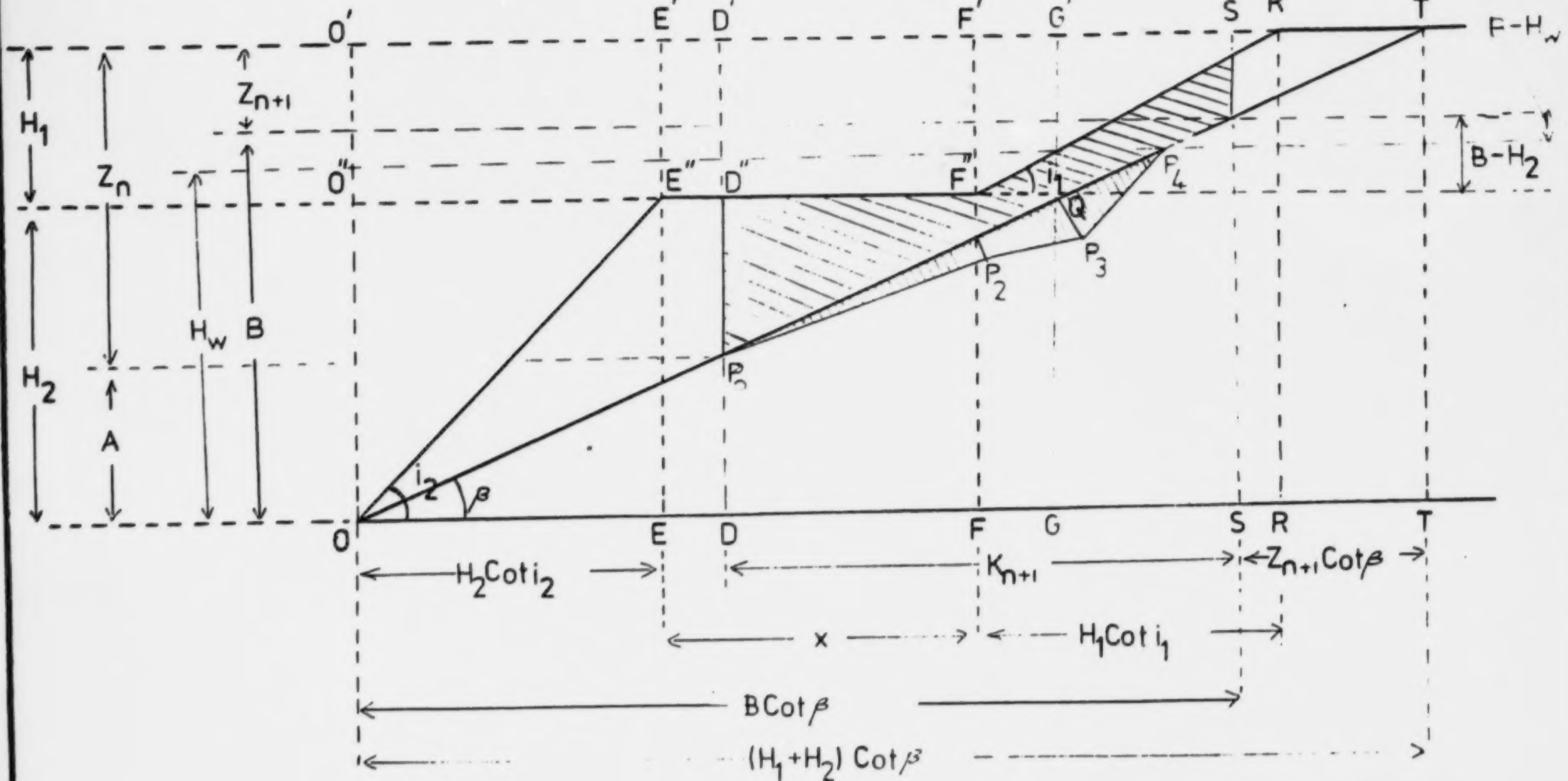
$$W = \frac{\gamma}{2} \left\{\cot \beta \left(Z_n{}^2 - Z_{n+1}{}^2\right) + H_1 \left(2 A \cot \beta - 2 H_2 \cot i_2 - H_1 \cot i_1 - 2x\right) + \left(H_2 \cot i_2 + x + H_1 \cot i_1 - B \cot \beta\right)^2 \tan \beta\right\}$$

4. Pressures

$\underline{P_0 = P_4 = 0, \; P_1 \text{ not required}}$

$$P_2 = \left(\gamma_w \quad H_2 - P_2F\right)$$

$$= \underline{\gamma_w \left\{H_2 \left(1 - \cot i_2 \tan \beta\right) - x \tan \beta\right\}}$$


O'
E'
D'
F'
G'
S'
R'
T'
F-H_w
H_1
Z_n
Z_{n+1}
O''
E''
D''
F''
i_1
Q
P_4
B-H_2
H_2
A
H_w
B
P_2
P_3
P_0
i_2
β
O
E
D
F
G
S
R
T
H_2 Cot i_2
K_{n+1}
Z_{n+1} Cot β
x
H_1 Cot i_1
B Cot β
(H_1+H_2) Cot β

CASE B2b

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG:32

$$P_3 = \gamma_w \left(H_w - P_3G\right) = \gamma_w \left(H_w - \tan\beta\,(H_2 \cot i_2 + x + H_1 \cot i_1 - GR)\right)$$

which is the same as case B.2.a.

$$= \underline{\gamma_w \left(H_w (1 - \cot i_1 \tan\beta) + \tan\beta \left[H_2 (\cot i_1 - \cot i_2) - x\right]\right)}$$

5. Areas

$$\underline{A_T = \frac{1}{\sin\beta} \left(B - A\right)}$$

$$\underline{(A_1 + A_2) = \frac{1}{\sin\beta} \left(H_2 \cot i_2 \tan\beta + x \tan\beta - A\right)}$$ (as case B.2.a.)

$$\underline{A_3 = \frac{1}{\sin\beta} \left(\cot i_1 \tan\beta\,(H_w - H_2)\right)}$$ (as case B.2.a.)

$$A_4 = \frac{1}{\sin\beta} \left(\tan\beta \left[H_2 (\cot i_1 - \cot i_2) - H_w \cot i_1 - x\right] + H_w\right)$$
(as case A.2.b.)

6. Uplift Force, U

$$\underline{U = \tfrac{1}{2} \left((A_1 + A_2)(P_0 + P_2) + A_3 (P_2 + P_3) + A_4 (P_3 + P_4)\right)}$$

7. Horizontal Force, V, due to water in the tension crack

$V = 0$

8. Resisting Force, Y, due to tensile strength across the potential crack

$$Y = T \left(Z_{n+1} (1 - \tan i_1 \cot \beta) - H_1 (1 + \tan i_1 \cot \beta) - H_2 \tan i_1 (\cot \beta + \cot i_2) - x \tan i_1\right)$$

Table 4 summarizes this formulae.

CASE B.2.c.

Figure 33 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(a) n th crack in the bench:-

$$H_2 \cot i_2 < \left(K_1 + K_2 ---- K_n\right) < H_2 \cot i_2 + x$$

(b) (n+1) th crack in the upper slope:-

$$H_2 \cot i_2 + x - A \cot \beta < K_{n+1} < H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$$

2. Conditions for the water table

Water table below H_2 $\quad$ $H_w < H_2$

When $H_w > H_2 (1 - \cot i_2 \tan i_1) + B \cot \beta \tan i_1 - x \tan i_1$

put $H_w = H_2 (1 - \cot i_2 \tan i_1) + B \cot \beta \tan i_1 - x \tan i_1$

3. Weight of the wedge, W

This is the same as case B.2.a. and is given by:-

$$W = \frac{\gamma}{2} \left(\cot \beta (Z_n^2 - Z_{n+1}^2) + H_1 (2 A \cot \beta - 2 H_2 \cot i_2 - H_1 \cot i_1 - 2x) + (H_2 \cot i_2 + x + H_1 \cot i_1 - B \cot \beta)^2 \tan \beta\right)$$

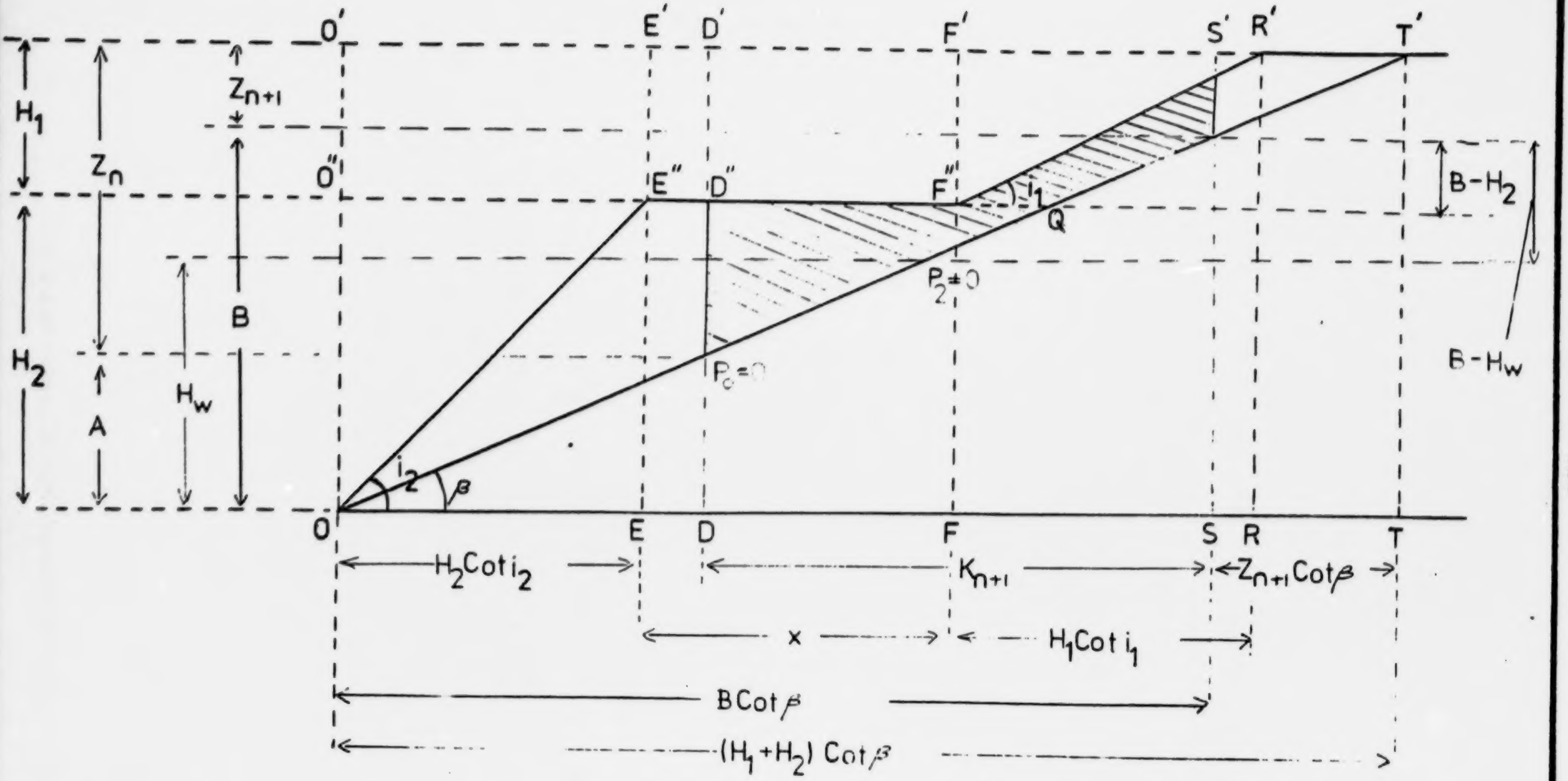
4. Pressures

$P_0 = P_1 = P_2 = P_3 = P_4 = 0$

5. Areas

$$A_T = \frac{1}{\sin \beta} \left(B - A\right)$$

A_1, A_2, A_3 and A_4 are not required since all pressures are zero.


O'
E'
D'
F'
S'
R'
T'
O"
E"
D"
F"
i_1
Q
$P_2 \neq 0$
$P_c = 0$
i_2
β
O
E
D
F
S
R
T
H_1
H_2
Z_n
A
Z_{n+1}
B
H_w
B-H_2
B-H_w
$H_2 \text{Cot} i_2$
K_{n+1}
$Z_{n+1} \text{Cot} \beta$
x
$H_1 \text{Cot} i_1$
$B \text{Cot} \beta$
$(H_1+H_2) \text{Cot} \beta$

CASE B2c

DWN. BY : K.B.
DATE :
SCALE : -
DWG. No.: FIG: 33

6. Uplift Force, U

$U = 0$

7. Horizontal Force, V, due to water in the tension crack

$V = 0$

8. Resisting Force, Y, due to tensile strength across the potential crack

$$Y = T \left\{ Z_{n+1} (1 - \tan i_1 \cot \beta) - H_1 (1 + \tan i_1 \cot \beta) - H_2 \tan i_1 (\cot \beta + \cot i_2) - x \tan i_1 \right\}$$

CASE B.3.a.

Figure 34 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(a) n th crack in the bench:-

$$\underline{H_2 \cot i_2 < \{K_1 + K_2 \text{ ---- } K_n\} < H_2 \cot i_2 + x}$$

(b) (n+1) th crack in the bench:-

(i) $\underline{A \cot \beta + K_{n+1} < H_2 \cot i_2 + x}$

(ii) $\underline{K_{n+1} > 0}$

i.e. $\underline{0 < K_{n+1} < H_2 \cot i_2 + x - A \cot \beta}$

2. Conditions for the water table

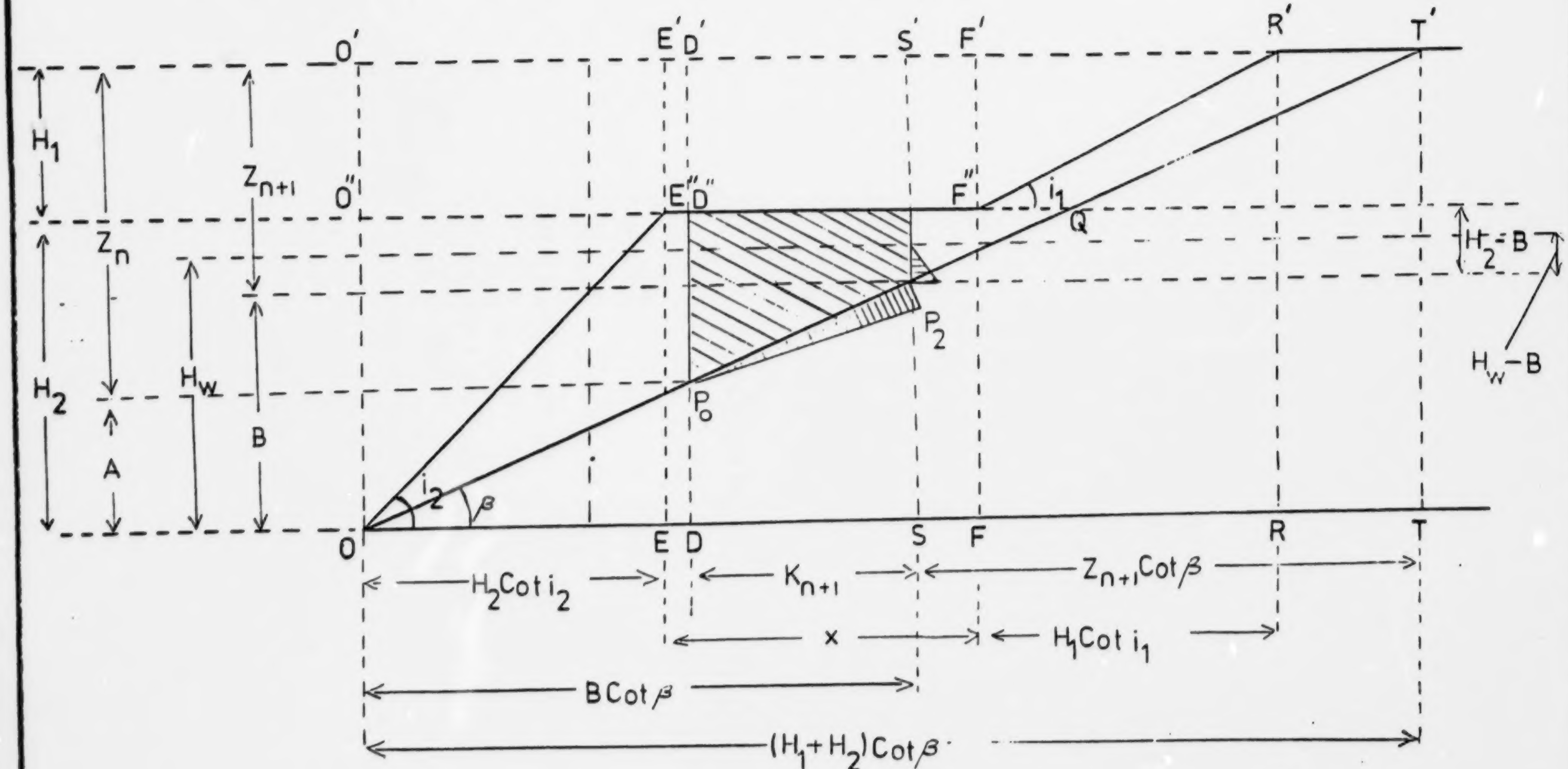
Water table above the bottom of the (n+1) th crack $\underline{H_w > B}$

When $H_w > H_2$ put $H_w = H_2$

3. Weight of the wedge, W

$$W = \gamma \{K_{n+1} (H_2 - B) + ½ K_{n+1} (B - A)\}$$

$$\underline{= \frac{\gamma}{2} K_{n+1} \{2 H_2 - 2 B + B - A\} = \frac{\gamma}{2} K_{n+1} \{2 H_2 - (B + A)\}}$$


O'
E'
D'
S'
F'
R'
T'
O''
E''
D''
F''
H_1
Z_n
Z_{n+1}
H_2
H_w
B
A
i_1
Q
P_2
P_o
$H_2 - B$
$H_w - B$
i_2
β
O
E
D
S
F
R
T
$H_2 \mathrm{Cot}\, i_2$
K_{n+1}
$Z_{n+1} \mathrm{Cot}\, \beta$
x
$H_1 \mathrm{Cot}\, i_1$
$B \mathrm{Cot}\, \beta$
$(H_1 + H_2) \mathrm{Cot}\, \beta$

CASE B 3a

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG: 34

4. Pressures

$P_0 = 0$, P_1, P_3, P_4 not required.

$P_2 = \gamma_w (H_w - B) = \gamma_w \alpha$

5. Areas

$$A_T = \frac{1}{\sin \beta} (B - A)$$

$$A_1 + A_2 = \frac{1}{\sin \beta} (B - A)$$

A_3 and A_4 not required.

6. Uplift Force, U

$U = \tfrac{1}{2} (P_0 + P_2)(A_1 + A_2)$

7. Horizontal Force, V, due to water in the tension crack

$V = \gamma_w \alpha^2/2$

8. Restraining Force, Y, due to tensile strength across the potential crack

$Y = T (Z_{n+1} - H_1)$

CASE B.3.b.

Figure 35 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(a) n th crack in the bench:-

$$\underline{H_2 \cot i_2 < \left\{K_1 + K_2 ---- K_n\right\} < H_2 \cot i_2 = x}$$

(b) (n+1) th crack in the bench:-

$$\underline{0 < K_{n+1} < H_2 \cot i_2 + x - A \cot} \ \beta$$

2. Conditions for the water table

Water table below bottom of (n+1) th crack:- $\underline{H_w < B}$

When $H_w > H_2$ put $H_w = H_2$

3. Weight of wedge, W

This is the same as case B.3.a. and is given by:-

$$\underline{W = \tfrac{1}{2}\gamma K_{n+1} \left\{2H_2 - (B + A)\right\}}$$

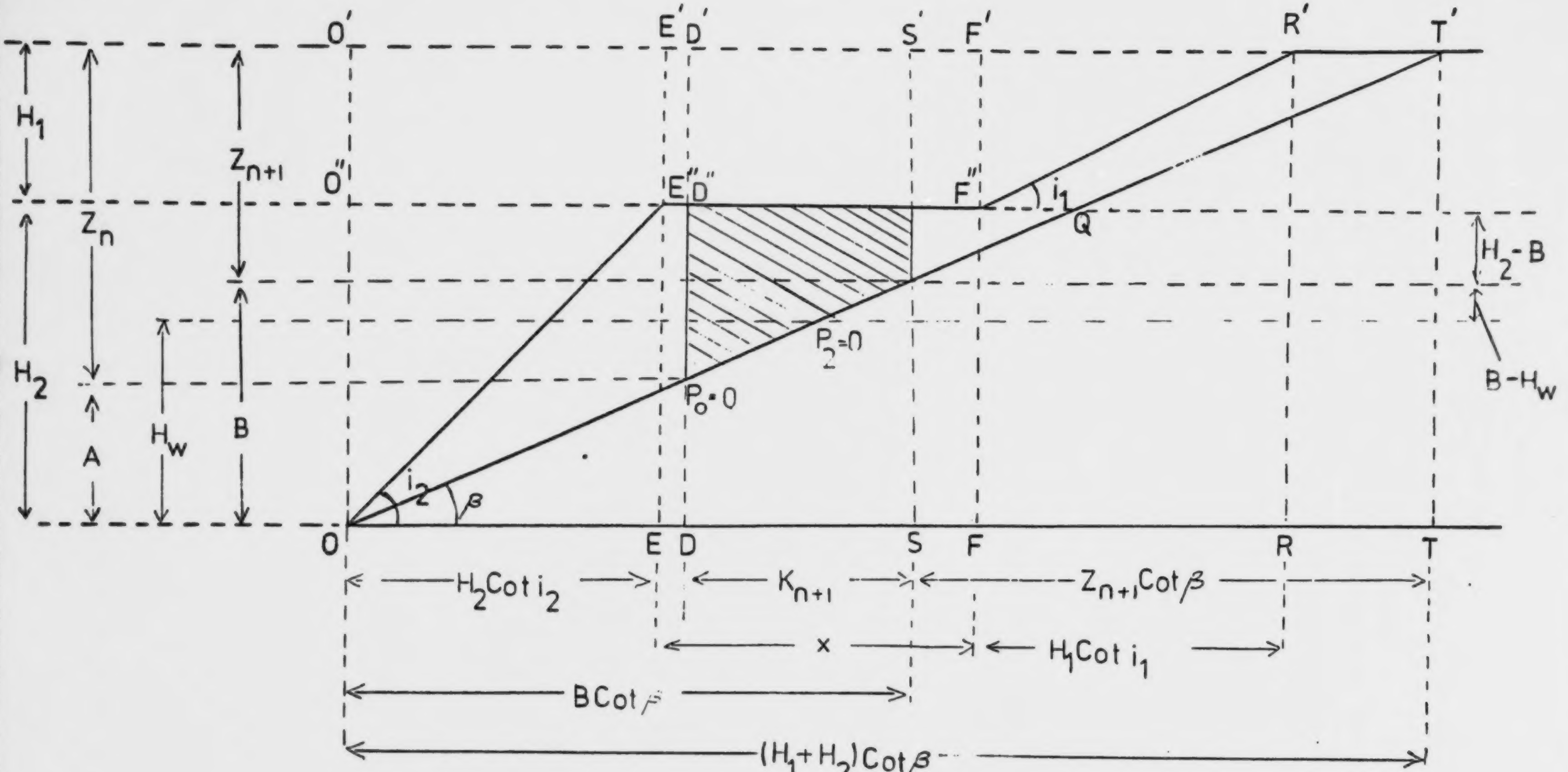
4. Pressures

$$\underline{P_0 = P_1 = P_2 = P_3 = P_4 = 0}$$

5. Areas

$$\underline{A_T = \frac{1}{\sin\ \beta}\left\{B - A\right\}}$$

Areas A_1, A_2, A_3 and A_4 not required since all pressures are zero.


O'
E'
D'
S'
F'
R'
T'
O''
E''
D''
F''
i_1
Q
H_1
Z_{n+1}
Z_n
H_2
A
H_w
B
H_2 - B
B - H_w
P_2=0
P_o=0
i_2
β
O
E
D
S
F
R
T
H_2Cot i_2
K_{n+1}
Z_{n+1}Cot β
x
H_1Cot i_1
BCot β
(H_1+H_2)Cot β

CASE B3b

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG: 35

6. Uplift Force, U

   $U = 0$

7. Horizontal Force, V, due to water in the tension crack

   $V = 0$

8. Restraining Force, Y, due to tensile strength across the potential crack

   $Y = T\left(Z_{n+1} - H_1\right)$

Table 4 summarizes these formulae.

CASE C.1.a.

Figure 36 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack position

(a) n th crack in the upper slope:-

$$H_2 \cot i_2 + x < \left(K_1 + K_2 + \text{----} K_n\right) < H_2 \cot i_2 + x + H_1 \cot i_1$$

(b) (n+1) th crack in the crest:-

(i) $A \cot \beta + K_{n+1} > H_2 \cot i_2 + x + H_1 \cot i_1$

(ii) $A \cot \beta + K_{n+1} < (H_1 + H_2) \cot \beta$

i.e. $H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta < K_{n+1} < (H_1 + H_2) \cot \beta - A \cot \beta$

2. Conditions for the water table

Water table above bottom of (n+1) th crack:- $H_W > B$

3. Weight of the wedge, W

$$W = \gamma \left(F''R''R' + R'R''S''S' - F''D''D''' - QS''P_4 + QD'''P_2\right)$$

$$= \frac{\gamma}{2} \left(H_1^2 \cot i_1 + 2 H_1 (B \cot \beta - H_1 \cot i_1 - x - H_2 \cot i_2) - (A \cot \beta - x - H_2 \cot i_2)^2 \tan i_1 - (B - H_2)^2 \cot \beta + (A - H_2)^2 \cot \beta\right)$$

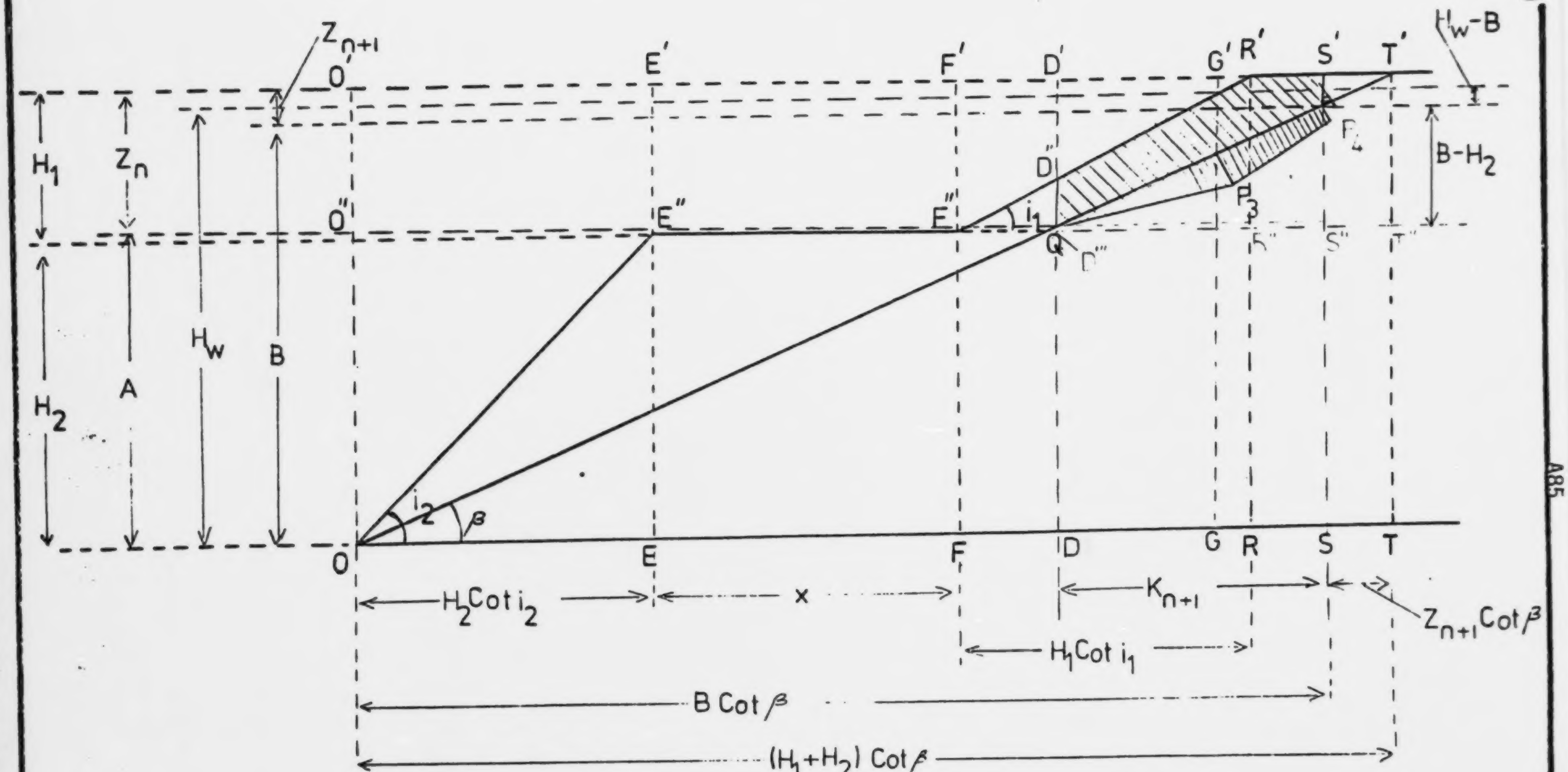
4. Pressures

P_0, P_1 not required.

$P_2 = 0$

$P_3 = \gamma_w \left(G'P_3 - G'R' \tan i_1\right) = \gamma_w \left(G'T' \tan \beta - G'R' \tan i_1\right)$

$= \gamma_w \left(R'T' \tan \beta + G'R' (\tan \beta - \tan i_1)\right)$


Z_{n+1}
O'
E'
F'
D'
G'
R'
S'
T'
H_w-B
H_1
Z_n
$B-H_2$
D''
P_4
O''
E''
F''
i_1
P_3
Q
D'''
R''
S''
T''
H_2
A
H_w
B
i_2
β
O
E
F
D
G
R
S
T
$H_2 \mathrm{Cot}\, i_2$
x
K_{n+1}
$Z_{n+1} \mathrm{Cot}\, \beta$
$H_1 \mathrm{Cot}\, i_1$
$B \mathrm{Cot}\, \beta$
$(H_1+H_2) \mathrm{Cot}\, \beta$

CASE C1a

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG: 36

$$= \gamma_w \left\{ \left[(H_1 + H_2) \cot \beta - H_1 \cot i_1 - x - H_2 \cot i_2 \right] \tan \beta + (\tan \beta - \tan i_1) \left[(H_1 + H_2 - H_w) \cot i_1 \right] \right\}$$

$$= \gamma_w \left\{ H_2 \tan \beta (\cot i_1 - \cot i_2) - x \tan \beta + H_w (1 - \cot i_1 \tan \beta) \right\}$$

$$P_4 = \gamma_w (H_w - B) = \gamma_w \alpha$$

5. Areas

$$A_T = \frac{1}{\sin \beta} \left(B - A \right)$$

A_1 and A_2 not required.

$$A_3 = \frac{1}{\sin \beta} \left(\tan \beta \, D'G' \right) = \frac{1}{\sin \beta} \left(\tan \beta \, (D'R' - R'G') \right)$$

$$= \frac{1}{\sin \beta} \left\{ \tan \beta \left[H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta - (H_1 + H_2 - H_w) \cot i_1 \right] \right\}$$

$$= \frac{1}{\sin \beta} \left(H_2 \cot i_2 \tan \beta + x \tan \beta - A - H_2 \cot i_1 \tan \beta + H_w \cot i_1 \tan \beta \right)$$

$$= \frac{1}{\sin \beta} \left(H_w \cot i_1 \tan \beta + x \tan \beta - A - H_2 \tan \beta (\cot i_1 - \cot i_2) \right)$$

$$A_4 = \frac{1}{\sin \beta} \left(\tan \beta \, G'S' \right) = \frac{1}{\sin \beta} \left(\tan \beta \left[B \cot \beta - H_2 \cot i_2 - x - F G \right] \right)$$

$$= \frac{1}{\sin \beta} \left(B - H_2 \cot i_2 \tan \beta - x \tan \beta - (H_w - H_2 \cot i_1 \tan \beta) \right)$$

$$= \frac{1}{\sin \beta} \left\{ B - H_2 \cot i_2 \tan \beta - x \tan \beta + H_2 \cot i_1 \tan \beta - H_w \cot i_1 \tan \beta \right\}$$

$$= \underline{\frac{1}{\sin \beta} \left\{ B - H_2 \tan \beta (\cot i_1 - \cot i_2) - \cot i_1 \tan \beta (H_w) - x \tan \beta \right\}}$$

6. Uplift Force, U

$$\underline{U = \tfrac{1}{2} \left((P_2 + P_3)A_3 + (P_3 + P_4)A_4 \right)}$$

7. Horizontal Force, V, due to water in the tension crack

$$\underline{V = P_4/_2\, \alpha = \gamma_w\, \alpha^2/_2}$$

8. Restraining Force, Y, due to tensile strength across the potential crack

$$\underline{Y = T\, Z_{n+1}}$$

Table 4 summarizes these formulae.

CASE C.1.b.

Figure 37 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(a) n th crack in the upper slope:-

$$\underline{H_2 \cot i_2 + x < \left(K_1 + K_2 + \text{----}\ K_n\right) < H_2 \cot i_2 + x + H_1 \cot i_1}$$

(b) (n+1) th crack in the crest:-

$$\underline{H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta < K_{n+1} < (H_1 + H_2) \cot \beta - A \cot \beta}$$

2. Conditions for the water table

Water table below bottom of (n+1) th crack:- $\underline{H_w < B}$

Water table above top of n th crack:-

$$H_w > A + F\,D \tan i_1$$

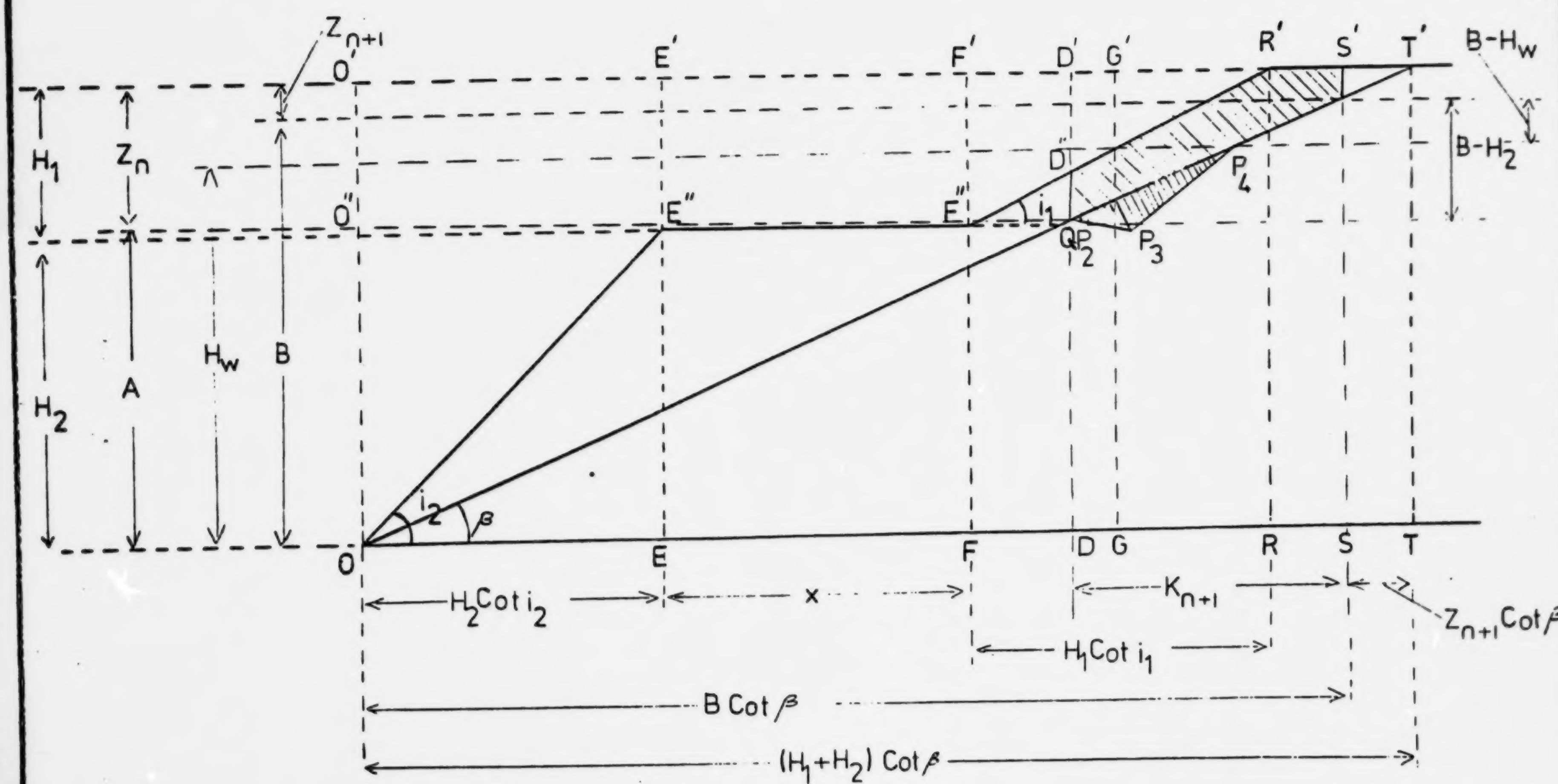
$$> A + \tan i_1 \,(A \cot \beta - x - H_2 \cot i_2)$$

i.e. $\underline{B > H_w > A\,(1 + \cot \beta \tan i_1) - x \tan \beta - H_2 \cot i_2 \tan \beta}$

3. Weight of the wedge, W

This is the same as case C.1.a. and is given by:-

$$\underline{\begin{aligned} W = \tfrac{\gamma}{2} \Big\{ & H_1^2 \cot i_1 + 2 H_1 (B \cot \beta - H_1 \cot i_1 - x - H_2 \cot i_2) - (A \cot \beta \\ & - x - H_2 \cot i_2)^2 \tan i_1 - (B - H_2)^2 \cot \beta + (A - H_2)^2 \cot \beta \Big\} \end{aligned}}$$


Z_{n+1}
O'
E'
F'
D'
G'
R'
S'
T'
$B-H_w$
H_1
Z_n
$B-H_2$
D''
P_4
O''
E''
E''
i_1
Q
P_2
P_3
H_2
A
H_w
B
i_2
β
O
E
F
D
G
R
S
T
$H_2 \cot i_2$
x
K_{n+1}
$Z_{n+1} \cot \beta$
$H_1 \cot i_1$
$B \cot \beta$
$(H_1+H_2) \cot \beta$

CASE C1b

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG:37

4. **Pressures**

P_0, P_1 are not required.

$P_2 = P_4 = 0$

$$P_3 = \gamma_w \{G'P_3 - G'R' \tan i_1\} \text{ which is the same as case C.1.a.}$$

$$= \gamma_w \{H_2 \tan \beta (\cot i_1 - \cot i_2) - x \tan \beta + H_w (1 - \cot i_1 \tan \beta)\}$$

5. **Areas**

$$A_T = \frac{1}{\sin \beta} \{B - A\}$$

A_1 and A_2 are not required.

$$A_3 = \frac{1}{\sin \beta} \{D'G' \tan \beta\} \text{ which is the same as case C.1.a.}$$

$$= \frac{1}{\sin \beta} \{H_w \cot i_1 \tan \beta + x \tan \beta - A - H_2 \tan \beta (\cot i_1 - \cot i_2))\}$$

$$A_4 = \frac{1}{\sin \beta} \{G'L' \tan \beta\} \text{ which is the same as case A.2.b.}$$

$$= \frac{1}{\sin \beta} \{\tan \beta \left[H_2 (\cot i_1 - \cot i_2) - H_w \cot i_1 - x\right] + H_w\}$$

6. **Uplift Force, U**

$$U = \tfrac{1}{2} \{(P_2 + P_3)A_3 + (P_3 + P_4)A_4\}$$

7. Horizontal Force, V, due to water in the tension crack

$V = 0$

8. Resisting Force, Y, due to tensile strength across the potential crack

$Y = T\ Z_{n+1}$

Table 4 summarizes this formulae.

CASE C.1.c.

Figure 38 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(a) n th crack in the upper slope:-

$$H_2 \cot i_2 + x < \left(K_1 + K_2 + \text{----} K_n\right) < H_2 \cot i_2 + x + H_1 \cot i_1$$

(b) (n+1) th crack in the crest:-

$$H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta < K_{n+1} < (H_1 + H_2) \cot \beta - A \cot \beta$$

2. Conditions for the water table

Water table below top of n th crack:-

$$H_w < A\ (1 + \cot \beta \tan i_1) - x \tan \beta - H_2 \cot i_2 \tan \beta$$

3. Weight of the wedge, W

This is the same as case C.1.a. and is given by:-

$$W = \frac{\gamma}{2} \left(H_1{}^2 \cot i_1 + 2 H_1 (B \cot \beta - H_1 \cot i_1 - x - H_2 \cot i_2) - (A \cot \beta - x - H_2 \cot i_2)^2 \tan i_1 - (B - H_2)^2 \cot \beta + (A - H_2)^2 \cot \beta\right)$$

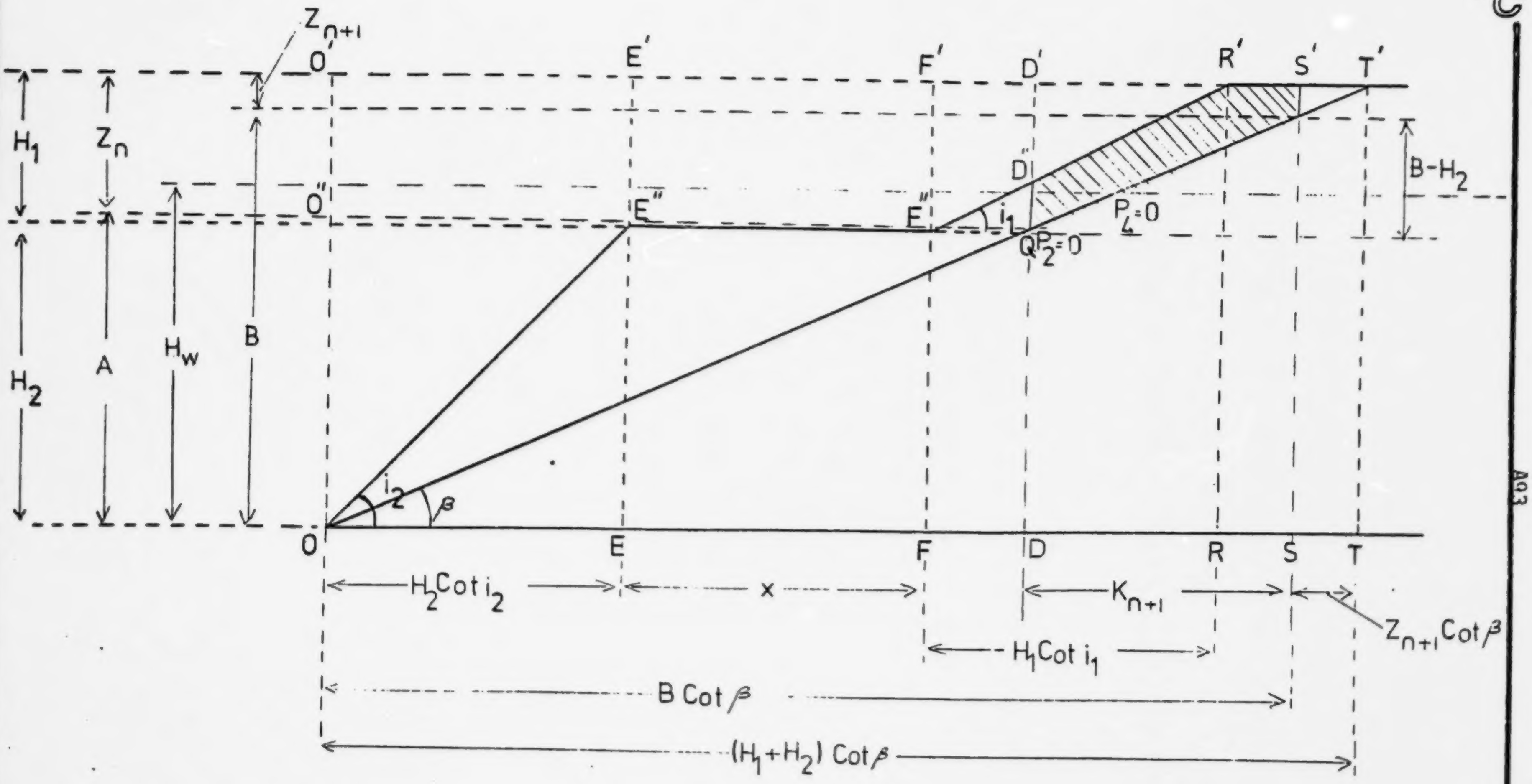
4. Pressures

$$P_0 = P_1 = P_2 = P_3 = P_4 = 0$$

5. Areas

$$A_T = \frac{1}{\sin \beta} \left(B - A\right)$$

A_1, A_2, A_3 and A_4 are not required since all pressures are zero.


Z_{n+1}
O'
E'
F'
D'
R'
S'
T'
H_1
Z_n
O''
E''
E''
D''
i_1
$P_4=0$
$QP_2=0$
$B-H_2$
H_2
A
H_w
B
i_2
β
O
E
F
D
R
S
T
$H_2 \cot i_2$
x
K_{n+1}
$Z_{n+1} \cot \beta$
$H_1 \cot i_1$
$B \cot \beta$
$(H_1+H_2) \cot \beta$

CASE C1c

DWN. BY : K.B.

DATE :

SCALE : -

DWG. No. : FIG: 38

6. Uplift Force, U

   $U = 0$

7. Horizontal Force, V, due to water in the tension crack

   $V = 0$

8. Restraining Force, Y, due to tensile strength across the potential crack

   $Y = T\ Z_{n+1}$

Table 4 summarizes these formulae.

CASE C.2.a.

Figure 39 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distributions.

1. Conditions for the crack positions

(a) n th crack in the upper slope:-

$$H_2 \cot i_2 + x < \left(K_1 + K_2 + \text{----} K_n\right) < H_2 \cot i_2 + x + H_1 \cot i_1$$

(b) (n+1) th crack in the upper slope:-

$$A \cot \beta + K_{n+1} < H_2 \cot {}_2 + x + H_1 \cot i_1$$

$$0 < K_{n+1} < H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$$

2. Conditions for the water table

Water table above bottom of (n+1) th crack:- $H_W > B$

When $H_W > H_2 (1 - \cot i_2 \tan i_1) + B \cot \beta \tan i_1 - x \tan i_1$

put $H_W = H_2 (1 - \cot i_2 \tan i_1) + B \cot \beta \tan i_1 - x \tan i_1$

3. Weight of the wedge, W

$$W = \gamma \left(F''S''S''' - F''D'''D'' - QS''P_4 + QD'''P_2\right)$$

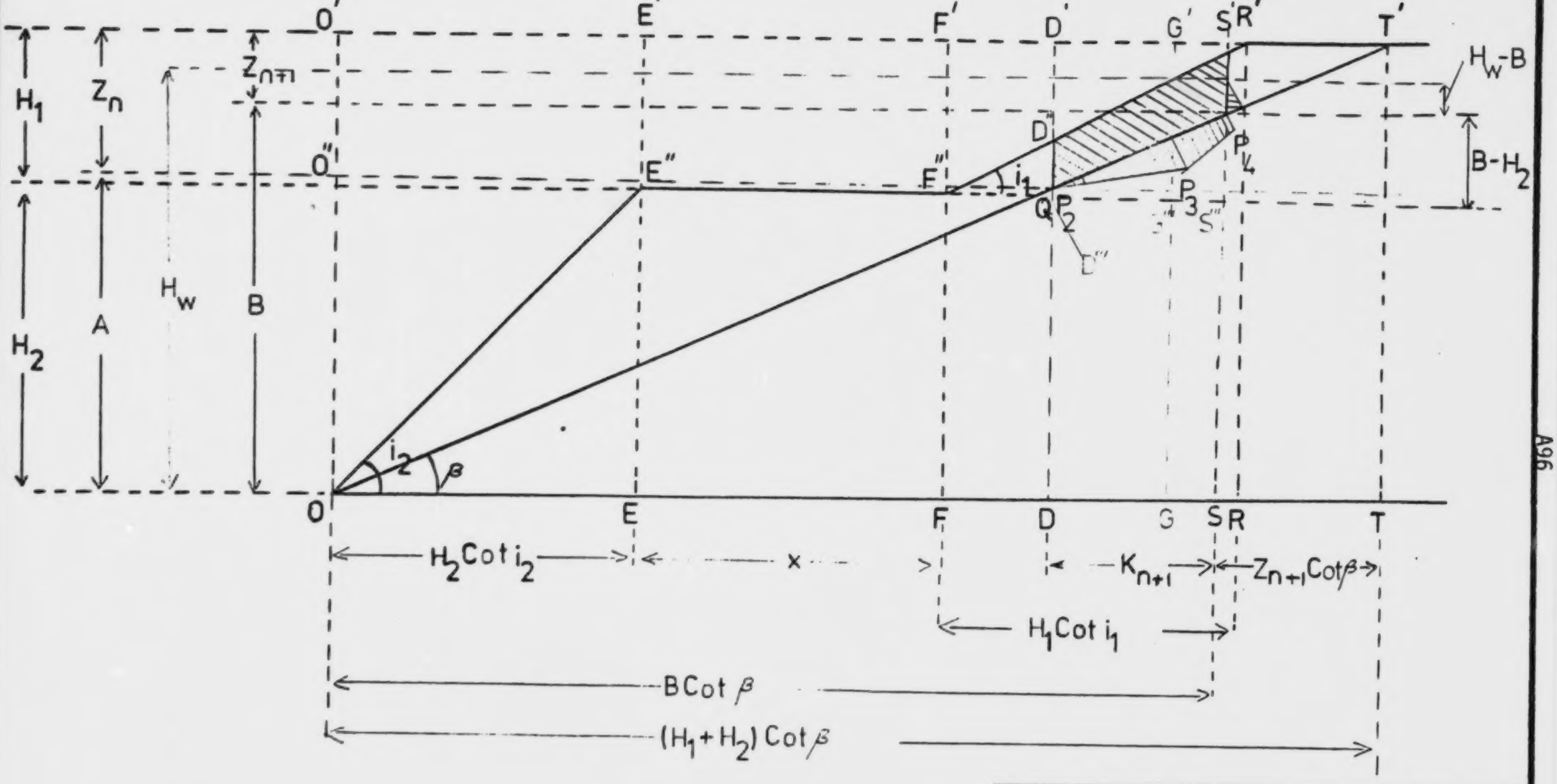
$$= \frac{\gamma}{2} \left((B \cot \beta - H_2 \cot i_2 - x)^2 \tan i_1 - (A \cot \beta - H_2 \cot i_2 - x)^2 \tan i_1 - (B - H_2)^2 \cot \beta + (A - H_2)^2 \cot \beta\right)$$

$$= \frac{\gamma}{2} \left(\tan i_1 \left[(B \cot \beta - H_2 \cot i_2 - x)^2 - (A \cot \beta - H_2 \cot i_2 - x)^2\right] - \cot \beta \left[(B - H_2)^2 - (A - H_2)^2\right]\right)$$

4. Pressures

P_0 and P_1 not required.

$P_2 = 0$


O'
E'
F'
D'
G'
S'R'
T'
H_1
H_2
Z_n
Z_{n+1}
A
H_w
B
O''
E''
F''
D''
i_1
Q
P_2
P_3
P_4
S'''
D'''
H_w-B
B-H_2
i_2
β
O
E
F
D
G
S
R
T
H_2 Cot i_2
x
K_{n+1}
Z_{n+1} Cot β
H_1 Cot i_1
B Cot β
(H_1+H_2) Cot β

CASE C 2a

DWN. BY : K.B.

DATE :

SCALE : -

DWG. No. : FIG: 39

$$P_3 = \gamma_w \left(G'P_3 - G'R' \tan i_1\right) = \gamma_w \left(G'T' \tan \beta - G'R' \tan i_1\right)$$

which is same as case C.1.a.

$$= \gamma_w \left(H_2 \tan \beta (\cot i_1 - \cot i_2) - x \tan \beta + H_w (1 - \cot i_1 \tan \beta)\right)$$

$$P_4 = \gamma_w (H_w - B) = \alpha \gamma_w$$

5. Areas

$$A_T = \frac{1}{\sin \beta} \left(B - A\right)$$

A_1 and A_2 not required.

$$A_3 = \frac{1}{\sin \beta} \left(D'G' \tan \beta\right) \qquad \text{which is same as case C.1.a.}$$

$$= \frac{1}{\sin \beta} \left(H_w \cot i_1 \tan \beta + x \tan \beta - A - H_2 \tan \beta (\cot i_1 - \cot i_2)\right)$$

$$A_4 = \frac{1}{\sin \beta} \left(G'S' \tan \beta\right)$$

$$= \frac{1}{\sin \beta} \left(\tan \beta (B \cot \beta - OG)\right)$$

$$= \frac{1}{\sin \beta} \left(\tan \beta (B \cot \beta - \left[H_2 \cot i_2 + x + FG\right])\right)$$

$$= \frac{1}{\sin \beta} \left(B - H_2 \cot i_2 \tan \beta - x \tan \beta - (H_w - H_2) \cot i_1 \tan \beta\right) = \frac{1}{\sin \beta} \left(B - H_2 (\cot i_1 - \cot i_2) \tan \beta - H_w \cot i_1 \tan \beta - x \tan \beta\right)$$

6. Uplift Force, U

$$U = ½ \left(A_3(P_2 + P_3) + A_4(P_3 + P_4)\right)$$

7. Horizontal Force, V, due to water in the tension crack

$$V = \frac{P_4}{2} (H_w - B) \gamma_w \alpha^2/2$$

8. Resisting Force, Y, due to tensile strength across the potential crack

$$\begin{aligned} Y &= T \left\{ Z_{n+1} - S'S''' \right\} = T \left\{ Z_{n+1} - S'R' \tan i_1 \right\} \\ &= T \left\{ Z_{n+1} - \tan i_1 (Z_{n+1} \cot \beta - RT) \right\} \\ &= T \left\{ Z_{n+1} (1 - \tan i_1 \cot \beta) + \tan i_1 \left[(H_1 + H_2) \cot \beta - H_1 \cot i_1 - x \right. \right. \\ &\qquad \left. \left. - H_2 \cot i_2 \right] \right\} \end{aligned}$$

Table 4 summarizes these formulae.

CASE C.2.b.

Figure 40 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(a) n th crack in the upper slope:-

$$H_2 \cot i_2 + x < \left(K_1 + K_2 + \cdots K_n\right) < H_2 \cot i_2 + x + H_1 \cot i_1$$

(b) (n+1) th crack in the upper slope:-

$$0 < K_{n+1} < H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$$

2. Conditions for the water table

(a) Below the bottom of the (n+1) th crack:- $H_W < B$

(b) Above top of the n th crack:-

$H_W > A + FD \tan i$ which is same as case C.1.b.

i.e. $H_W > A\,(1 + \cot \beta \tan i_1) - x \tan \beta - H_2 \cot i_2 \tan \beta$

When $H_W > H_2\,(1 - \cot i_2 \tan i_1) + B \cot \beta \tan i_1 - x \tan i_1$

put $H_W = H_2\,(1 - \cot i_2 \tan i_1) + B \cot \beta \tan i_1 - x \tan i_1$

3. Weight of the wedge, W

This is the same as case C.2.a. and is given by:-

$$W = \frac{\gamma}{2}\left(\tan i_1 \left[(B \cot \beta - H_2 \cot i_2 - x)^2 - (A \cot \beta - H_2 \cot i_2 - x)^2\right] - \cot \beta \left[(B - H_2)^2 - (A - H_2)^2\right]\right)$$

4. Pressures

P_0 and P_1 not required.

$P_2 = P_4 = 0$

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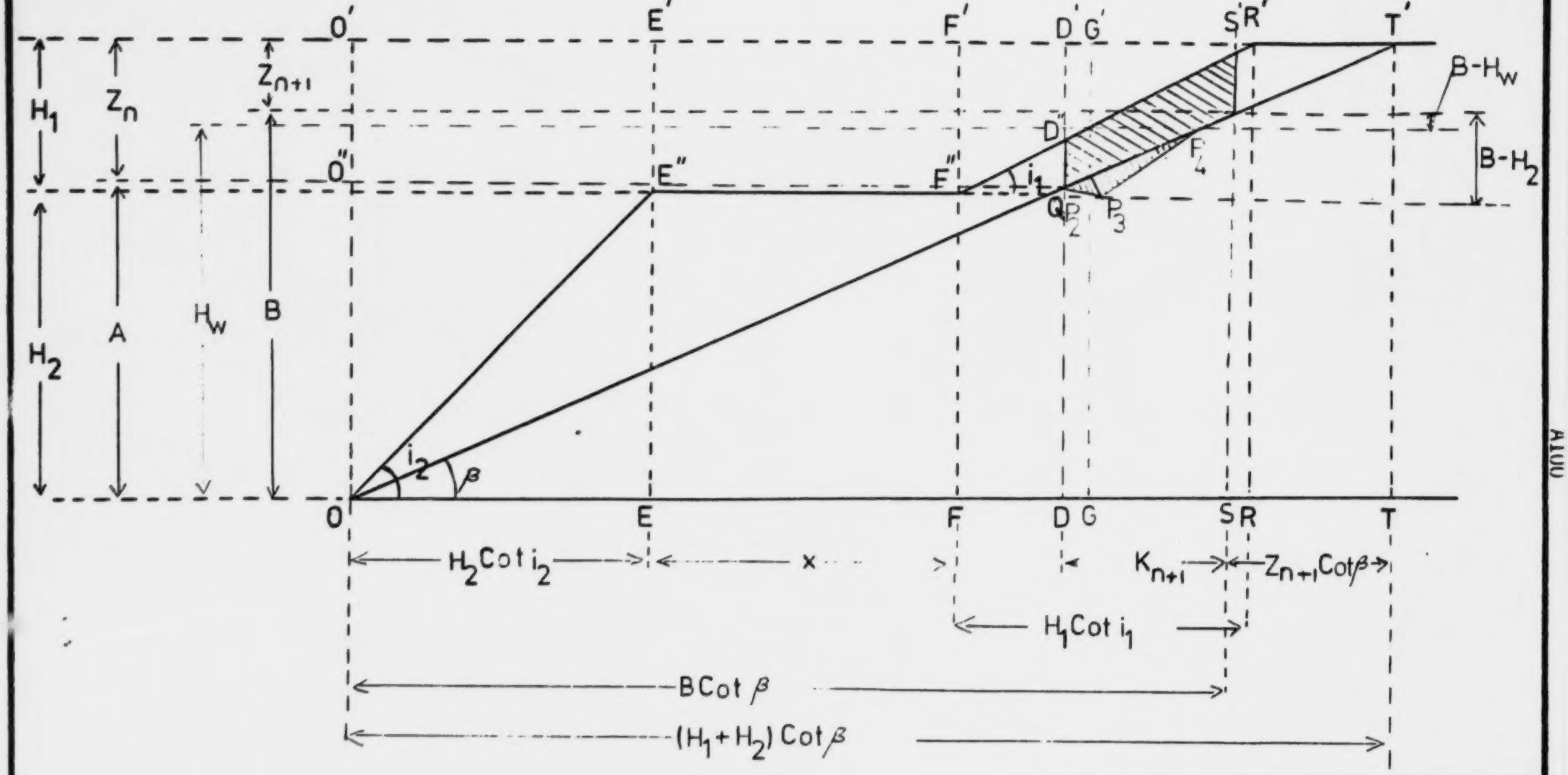
A100


O'
E'
F'
D' G'
S R'
T'
H1
Zn
Zn+1
O''
E''
F''
D''
i1
F4
Q P2 P3
B-Hw
B-H2
H2
A
Hw
B
i2
β
O
E
F
D G
S R
T
H2 Cot i2
x
Kn+1
Zn+1 Cot β
H1 Cot i1
B Cot β
(H1+H2) Cot β

CASE C 2b

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG: 40

$$P_3 = \gamma_w (G'P_3 - G'R' \tan i_1) \qquad \text{which is same as case C.2.a.}$$

$$= \gamma_w \left\{ H_2 \tan \beta (\cot i_1 - \cot i_2) - x \tan \beta + H_w (1 - \cot i_1 \tan \beta) \right\}$$

5. Areas

$$A_T = \frac{1}{\sin \beta} \left\{ B - A \right\}$$

A_1 and A_2 not required.

$$A_3 = \frac{1}{\sin \beta} \left\{ D'G' \tan \beta \right\} \qquad \text{which is same as case C.1.a.}$$

$$= \frac{1}{\sin \beta} \left\{ H_w \cot i_1 \tan \beta + x \tan \beta - A - H_2 \tan \beta (\cot i_1 - \cot i_2) \right\}$$

$$A_4 = \frac{1}{\sin \beta} \left\{ G'L' \tan \beta \right\} \qquad \text{which is same as case A.2.b.}$$

$$= \frac{1}{\sin \beta} \left\{ \tan \beta \left[H_2 (\cot i_1 - \cot i_2) - H_w \cot i_1 - x \right] + H_w \right\}$$

6. Uplift Force, U

$$U = \tfrac{1}{2} \left\{ (p_2 + P_3)A_3 + (P_3 + P_4)A_4 \right\}$$

7. Horizontal Force, V, due to water in the tension crack

$V = 0$

8. Restraining Force, Y, due to tensile strength across the potential tension crack

This is the same as case C.2.a.

$$Y = T \left\{ Z_{n+1} (1 - \tan i_1 \cot \beta) + \tan i_1 \left[(H_1 + H_2) \cot \beta - H_1 \cot i_1 \right] \right\}$$
$$- x - H_2 \cot i_2$$

Table 4 summarizes these formulae.

CASE C.2.c.

Figure 41 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(a) n th crack in the upper slope:-

$$H_2 \cot i_2 + x < \left(K_1 + K_2 ---- K_n\right) < H_2 \cot i_2 + x + H_1 \cot i_1$$

(b) (n+1) th crack in upper slope:-

$$0 < K_{n+1} < H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$$

2. Conditions for the water table

Below top of n th crack:-

$$H_w < A(1 + \cot \beta \tan i_1) - x \tan \beta - H_2 \cot i_2 \tan \beta$$

When $H_w > H_2 (1 - \cot i_2 \tan i_1) + B \operatorname{Cot} \beta \tan i_1 - x \tan i_1$

put $H_w = H_2 (1 - \operatorname{Cot} i_2 \tan i_1) + B \operatorname{Cot} \beta \tan i_1 - x \tan i_1$

3. Weight of the wedge, W

This is the same as case C.2.a. and is given by:-

$$W = \frac{\gamma}{2} \left(\tan i_1 \left[(B \cot \beta - H_2 \cot i_2 - x)^2 - (A \cot \beta - H_2 \cot i_2 - x)^2\right] - \cot \beta \left[(B - H_2)^2 - (A - H_2)^2\right]\right)$$

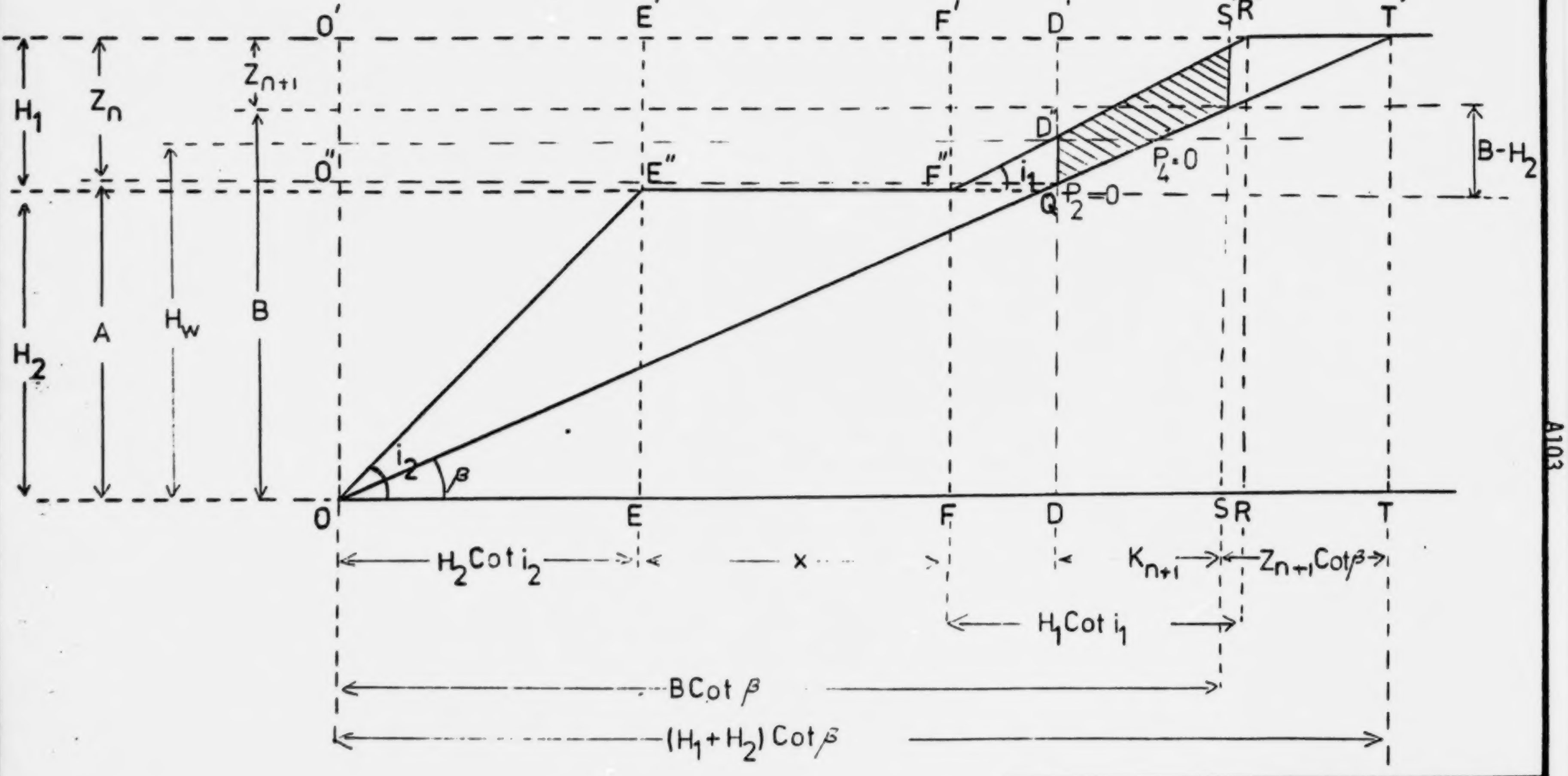
4. Pressures

$P_0 = P_1 = P_2 = P_3 = P_4 = 0$

5. Areas

$$A_T = \frac{1}{\sin \beta} \left(B - A\right)$$

A_1, A_2, A_3 and A_4 not required since all pressures are zero.


O'
E'
F'
D'
S
R'
T'
H_1
Z_n
Z_{n+1}
O''
E''
F''
D''
i_1
P_4=0
Q
P_2=0
B-H_2
H_2
A
H_w
B
i_2
β
O
E
F
D
S
R
T
H_2 Cot i_2
x
K_{n+1}
Z_{n+1} Cot β
H_1 Cot i_1
B Cot β
(H_1+H_2) Cot β

CASE C 2c

DWN. BY : K.B.	DATE :
SCALE : -	DWG. No. : FIG: 41

6. Uplift Force, U

$U = 0$

7. Horizontal Force, V, due to water in the tension crack

$V = 0$

8. Restraining Force, Y, due to tensile strength across the potential crack

This is the same as case C.2.a.

$$Y = T \left\{ Z_{n+1} (1 - \tan i_1 \cot \beta) + \tan i_1 \left[(H_1 + H_2) \cot \beta - H_1 \cot i_1 - x - H_2 \cot i_2 \right] \right\}$$

Table 4 summarizes these formulae.

CASE D.1.a.

Figure 42 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack positions

(a) n th crack in the crest:-

$$H_2 \cot i_2 + x + H_1 \cot i_1 < \left\{K_1 + K_2 ---- K_n\right\} < (H_1 + H_2) \cot \beta$$

(b) (n+1) th crack in the crest:-

(a) $A \cot \beta + K_n > H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$

i.e. $0 < K_{n+1} < (H_1 + H_2) \cot \beta - A \cot \beta$

2. Conditions for the water table

Above bottom of (n+1) th crack:- $H_w > B$

3. Weight of the wedge, W

$$W = \gamma\left(D'P_2T' - S'P_4T'\right)$$

$$= \frac{\gamma}{2} \cot \beta \left\{Z_n^2 - Z_{n+1}^2\right\}$$

4. Pressures

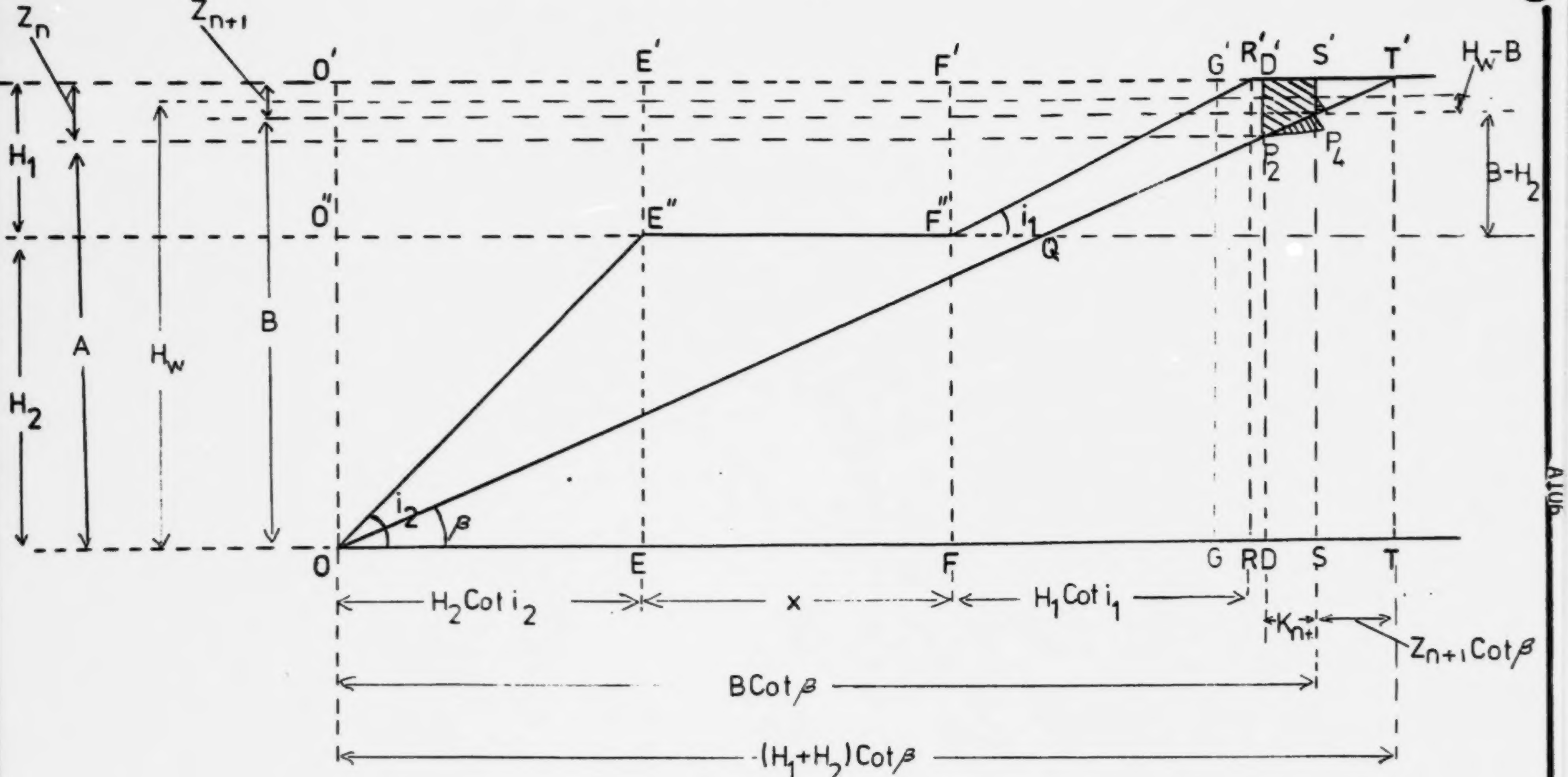
P_0, P_1, P_3 not required.

$P_2 = 0$

$P_4 = \gamma_w \alpha$

CMRC

A106


Z_n
Z_n+1
O'
E'
F'
G'
R'
D'
S'
T'
H_w-B
H_1
O"
E"
F"
i_1
Q
P_2
P_4
B-H_2
H_2
A
H_w
B
i_2
β
O
E
F
G
R
D
S
T
H_2 Cot i_2
x
H_1 Cot i_1
K_n+1
Z_n+1 Cot β
B Cot β
(H_1+H_2) Cot β

CASE D1a

DWN. BY : K.B.

DATE :

SCALE : -

DWG. No. : FIG: 42

5. Areas

$$A_T = \frac{1}{\sin\beta}\left(B - A\right)$$

A_1, A_2 not required.

$$A_3 + A_4 = \frac{1}{\sin\beta}\left(D'S' \tan\beta\right) = \frac{1}{\sin\beta}\left(K_{n+1} \tan\beta\right)$$

6. Uplift Force, U

$$U = ½\left((A_3 + A_4)(P_2 + P_4)\right)$$

7. Horizontal Force, V, due to water in the tension crack

$$V = \gamma_w \alpha^2/_2$$

8. Restraining Force, Y, due to tensile strength across the potential crack

$$Y = T Z_{n+1}$$

Table 4 summarizes these formulae.

CASE D.1.b.

Figure 43 illustrates this case, gives some of the relevant dimensions, the positions of the water pressures acting and the resulting water pressure distribution.

1. Conditions for the crack position

(a) n th crack in the crest:-

$$H_2 \cot i_2 + x + H_1 \cot i_1 < \left(K_1 + K_2 + \cdots K_n\right) < (H_1 + H_2) \cot \beta$$

(b) (n+1) th crack in the crest:-

$$0 < K_{n+1} < (H_1 + H_2) \cot \beta - A \cot \beta$$

2. Conditions for the water table

Below bottom of the (n+1) th crack:- $H_W < B$

3. Weight of the wedge, W

This is the same as case D.1.a. and is given by:-

$$W = \frac{\gamma}{2} \cot \beta \left(Z_n{}^2 - Z_{n+1}{}^2\right)$$

4. Pressures

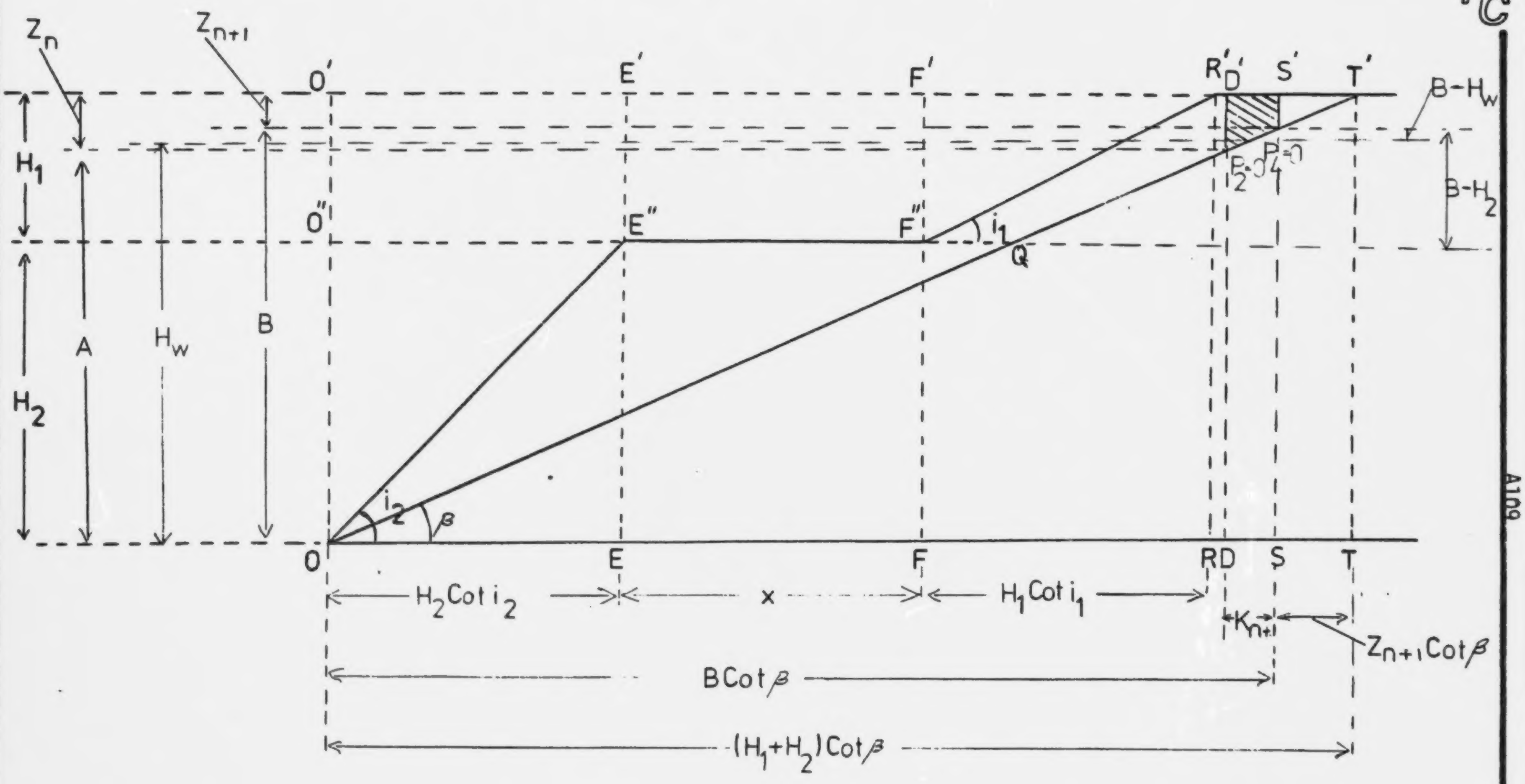
$$P_0 = P_1 = P_2 = P_3 = P_4 = 0$$

5. Areas

$$A_T = \frac{1}{\sin \beta} \left(B - A\right)$$

6. Uplift Force, U

$U = 0$


CMRC
Z_n
Z_{n+1}
O'
E'
F'
R'
D'
S'
T'
B-H_w
H_1
O''
E''
F''
i_1
Q
P_2·04
P=0
B-H_2
A
H_w
B
H_2
i_2
β
O
E
F
RD
S
T
H_2 Cot i_2
x
H_1 Cot i_1
K_{n+1}
Z_{n+1} Cot β
B Cot β
(H_1+H_2) Cot β

CASE D1b

DWN. BY : K.B.

DATE :

SCALE : -

DWG. No. : FIG: 43

7. Horizontal Force, V, due to water in the tension crack

$V = 0$

8. Restraining force, Y, due to tensile strength across the potential crack

$Y = T\ Z_{n+1}$

Table 4 summarizes these formulae.

Volume

2

7 of 12

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COAL MINING RESEARCH CENTRE

MULTIPLE BLOCK PLANE SHEAR SLOPE FAILURE
PART II: COMPUTER PROGRAM

by

K. BARRON, B. STIMPSON and K. KOZAR

CMRC REPORT 84/31-C MAR.1985

FINAL REPORT - VOLUME II

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AUG 15 1986

MICROMEDIA

CONTENTS

PAGE

1. Introduction 1
2. Description 2
3. Input data 9

Appendix A: Computer Program listing

Appendix B: Sample runs

MBPSSF

MULTIPLE BLOCK PLANE SHEAR SLOPE FAILURE

USER'S MANUAL

Authors: K. Barron and B. Stimpson

Coded by: K.M. Kosar

Date: July 1984

Language: FORTRAN IV

Introduction

This program* performs the analysis of multiple block plane shear failure for pit walls comprizing two slopes with an intervening bench, with a horizontal water table.

The "MTS" commands to run the MBPSSF program are:

```
$RUN *FORTGTEST SCARDS=MBPSSF T=5 (only required for initial run)

$RENAME -LOAD# CMBPSSF (only required for initial run)

DEBUG CMBPSSF 1=INPUT1 2=OUTPUT1 3=INPUT2 4=OUTPUT2 5=INPUT3
6=OUTPUT3 7=OUTPUT4 8=OUTPUT5 T=10
```

---

* VOLUME 1 of this report gives the theory and the computer program logic diagrams.

Description

The program requires input defining: the number of consecutive runs required; the type of analysis for each individual run (probabilistic or deterministic); the geometry of the problem; the engineering properties of the materials present; the number of solutions required; the set of units desired (S.I. or Imperial); and the statistical parameters required for the probabilistic analyses. The geometry, material properties and statistical information are provided to the program prior to execution. The number of program runs required, the type of analysis to be performed for each individual run and the solution number may be provided prior to execution or may be given interactively as execution proceeds.

MBPSSF consists of a main program and several subroutine subprograms. Each section of the program is summarized as follows:

Main Program

The main program performs the following tasks:

i) Sets the input output file numbers.

The MBPSSF program uses the following I/O units:

Fortran Unit	MTS Unit	File Name/Description	
		Interactive	Non Interactive
1	1	*MSOURCE*	Any permanent input file containing specification of the number of consecutive runs required and the type of analysis

			for each run.
2	2	*MSINK*	Temporary output file containing unrequired data.
3	3	*MSOURCE*	Any permanent input file containing solution numbers.
4	4	*MSINK*	Temporary output file containing unrequired data.
5	5	Permanent input file containing geometric, material property and statistical data.	
6	6	Permanent or temporary output file containing problem input data and problem solution.	
7	7	Permanent or temporary output file containing a table which summarizes, for the lower limit, the number and position of cracks found for each run.	
8	8	Permanent or temporary output file containing a table which	

summarizes, for the upper limit,
the number and position of cracks
found for each run.

ii) Reads the number of consecutive runs required.

iii) Initializes parameters and arrays.

iv) Reads and sets output units (S.I. or Imperial).

v) Calls subroutine subprogram DATA to receive input data.

vi) Reads the type of analysis for each run (probabilistic or deterministic).

vii) If the probabilistic option is selected, reads statistical parameters and randomly selects from normal distributions values for the angle of failure plane with the horizontal, the tensile strength of the rock, the effective cohesion on the failure plane and the effective angle of friction on the failure plane.

viii) Terminates execution if geometry is such that the problem must be analysed as two separate slopes.

ix) Advances the horizontal distance between the nth and (n+1)th cracks by the increment specified in input and calculates depth of the (n+1)th crack below the surface.

x) Calculates the position of the nth crack and directs execution to the appropriate subroutine subprogram (Case A, B, C or D) for analysis. Terminates execution if slope analysis is complete.

xi) Writes summary tables for the lower and upper limits of safety factors.

Subroutine subprograms DATASI and DATAIM

Subroutine DATASI or DATAIM is called from MAIN and carries out the following:

i) Terminates program execution if no data is found in the input file assigned to fortran unit 5.

ii) Prints output heading in output file assigned to fortran unit 6.

iii) Reads from input file assigned to fortran unit 5: problem title; geometric data; and material properties.

iv) Prints: problem title; geometric data; and material properties in output file assigned to fortran unit 6.

v) Converts angles from degrees to radians for calculations.

Subroutine subprograms CASEA, CASEB, CASEC and CASED

Subroutines CASEA, CASEB, CASEC and CASED are called from MAIN. Each subprogram:

i) Terminates execution if the (n+1)th crack does not fall within the failure wedge.

ii) Depending on the position of the (n+1)th crack, directs execution of the program to the appropriate subroutine for calculation of: weight of the failed wedge between nth and (n+1)th cracks; total area of the failure plane, of unit width, between the nth and (n+1)th cracks; total uplift force due to water pressure acting on the failure plane between the nth and (n+1)th cracks; force applied to the failed wedge by water in the (n+1)th crack; and the resisting force due to tensile strength across the potential (n+1)th crack.

Subroutine subprograms SUB1,SUB2,...SUB10

Subroutines SUB1 through SUB10 are called as follows:

Subroutine	Description	Called from
SUB1	Case A1	CASEA
SUB2	Case A2	CASEA
SUB3	Case A3	CASEA
SUB4	Case A4	CASEA
SUB5	Case B1	CASEB
SUB6	Case B2	CASEB
SUB7	Case B3	CASEB
SUB8	Case C1	CASEC
SUB9	Case C2	CASEC
SUB10	Case D1	CASED

Based on the position of the water table, these subprograms calculate the parameters set out in section 3(ii). After these values are determined, subroutine subprogram SUB11 is called and the stability calculations are performed on the wedge defined by the nth and (n+1)th cracks.

Subroutine subprograms SUB11S and SUB11I

Subroutine SUB11S or SUB11I is called from any of subroutines SUB1 through SUB10 and performs the following:

i) Calculates the factor of safety.

ii) If the factor of safety falls outside the prescribed limits (0.99 to 1.01), control is transfered back through the intervening subroutines to the main program where the horizontal distance between the nth and (n+1)th cracks is increased by the prescribed incremental horizontal distance.

iii) If the factor of safety falls within the prescribed limits it prints (for the upper and lower limits): the position and depth of the tension crack; parameters as calculated by the appropriate subroutine (SUB1 through SUB10); and solution number in the output file assigned to fortran unit 6. If the first solution is being considered, the program will either continue with the first solution or search for a second solution as set out in fortran unit 4. This is either done interactively by the user or as prescribed in a permanent file attached to fortran unit 4. If the first solution is to be continued, the (n+1)th crack becomes the nth crack and control is transfered through the intervening subroutines back to the main program where a new (n+1)th crack is then sought. If it is desirable to search for a second solution, execution is directed again back to the main program where the horizontal distance between the nth and (n+1)th cracks is increased by the prescribed horizontal distance. If the second solution is being considered, control is transfered back through the intervening subroutines to the main program where the (n+1)th crack becomes the nth crack and a new (n+1)th crack is then sought.

Function RAND

Function RAND is a portable random number generator which uses the recursion IX = IX*A mod P.

Reference: Schrage, L. "A More Portable Fortran Random Number Generator". ACM Transactions on Mathematical Software, Vol. 5, No. 2, June 1979, pp 132-138.

Functions RNORMB, RNORMP, RNORMC, RNORMT

These functions are used to obtain random samples from normal distributions for: the angle of the failure plane with the horizontal (RNORMB); the tensile strength of the rock (RNORMT); the effective cohesion on the failure plane (RNORMC); and the effective angle of friction on the failure plane (RNORMP).

Reference:Pritsker , A.A.B. & Pegden, C.D. "Introduction to Simulation and Slam". John Wiley & Sons Inc., New York, 1979. p 566.

Input Data

FORTRAN UNIT 5

I UNITS CARD (G20.0)

columns	variable	entry
free format with commas	NUNIT	0 Imperial 1 S.I.

II HEADING CARD (20A4)

columns	variable	entry
1 - 80	TITLE(20)	Enter the title information for use in labeling the output

III GEOMETRIC DATA CARDS

Card 1 (4G20.0)

columns	variable	entry
free format with commas	H1	Height of the upper slope (m or ft)
	H2	Height of the lower slope (m or ft)
	HW	Height of the water table (m or ft)
	XB	Bench width (m or ft)

Card 2 (3G20.0)

columns	variable	entry
free format with commas	AI1	Angle of upper slope with the horizontal (deg)
	AI2	Angle of lower slope with the horizontal (deg)
	BETA	Angle of the failure plane with the horizontal (deg)

Card 3 (G20.0)

columns	variable	entry
free format with commas	DELTA	Incremental horizontal distance (m or ft)

IV MATERIAL PROPERTIES CARD (5G20.0)

columns	variable	entry
free format	T	Tensile strength of the rock (kPa or psf)
with commas	C	Effective cohesion on the failure plane (kPa or psf)
	GAMMA	Density of rock in failed wedge (kN/m3 or pcf)
	GAMMAW	Density of water (kN/m3 or pcf)

	PHI	Effective angle of friction on the failure plane (deg)

V STATISTICAL PARAMETERS CARD (4G20.0)

columns	variable	entry
free format	STBETA	Standard deviation of angle of failure plane with the horizontal
with commas	STT	Standard deviation of tensile strength of the rock
	STC	Standard deviation of effective cohesion on the failue plane
	STPHI	Standard deviation of effective angle of friction on the failure plane

FORTRAN UNIT 3

I SOLUTION NUMBER (I1)

a) Interactive Mode

columns	variable	entry
1	IS	Solution number as prompted by program "Do you wish to continue with solution 1 or search for solution 2 - Enter 1 or 2"

b) Prescribed Prior to Execution

Card 1 (I1)

columns	variable	entry
1	IS	1 or 2

Card 2 (I1)

columns	variable	entry
1	IS	1 or 2
.	.	.
.	.	.
.	.	.

Card N (I1)

columns	variable	entry
1	IS	1 or 2

FORTRAN UNIT 1

I NUMBER OF CONSECUTIVE RUNS CARD (I2)

a) Interactive Mode

columns	variable	entry
1-2	NRUN	Number of consecutive runs as prompted by program "How many successive program runs are required? (maximum of 99) for example: if 8 runs are required, enter 08"

b) Prescribed Prior to Execution

columns	variable	entry
1-2	NRUN	maximum of 99 runs

II TYPE OF ANALYSIS CARDS (I1)

a) Interactive Mode

columns	variable	entry
1	ITOA	Type of analysis as prompted by program "Option 1: Probabilistic Option 2: Deterministic - Enter 1 or 2"

b) Prescribed Prior to Execution

Card 1 (I1)

columns	variable	entry
1	ITOA	1 or 2

Card 2 (I1)

columns	variable	entry
1	ITOA	1 or 2
.	.	.
.	.	.
.	.	.

Card N (I1)

columns	variable	entry
1	ITOA	1 or 2

Appendix A

Appendix A contains a listing of computer program MBPSSF.

Appendix B

Appendix B contains some sample problems.

APPENDIX A - Computer Program MBPSSF

```
    1.000               C
    2.000               C
    3.000               C
    4.000               C      * * * * * * * * * * * * * * * * * * * * * * * * * * * *
    5.000               C      *                                                     *
    6.000               C      *                     MBPSSF                          *
    7.000               C      *     Multiple Block Plane Shear Slope Failure        *
    8.000               C      *                                                     *
    9.000               C      * * * * * * * * * * * * * * * * * * * * * * * * * * * *
   10.000               C
   11.000               C      A computer program to perform the analysis of multiple
   12.000               C      block plane shear failure for pit walls comprizing two
   13.000               C      slopes with an intervening bench, with a horizontal
   14.000               C      water table.
   15.000               C
   16.000               C                        Developed by:
   17.000               C
   18.000               C      K. Barron                           B. Stimpson
   19.000               C      Coal Mining Research Center         Dept. of Mineral Engineering
   20.000               C      EDMONTON, Alberta                   University of Alberta
   21.000               C                                          EDMONTON, Alberta
   22.000               C
   23.000               C
   24.000               C      ************************************************************
   25.000               C      Dimensions
   26.000               C      ************************************************************
   27.000               C
   28.000     0001             IMPLICIT REAL*8(A-H,K,O-Z)
   29.000     0002             INTEGER ICNO/'A1'/
   30.000     0003             COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
   31.000                     *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
   32.000                     *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
   33.000                     *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
   34.000     0004             REAL DTU(100),DTL(100)
   35.000               C
   36.000               C      ************************************************************
   37.000               C      Set Input/Output File Numbers and Initialize
   38.000               C      ************************************************************
   39.000               C
   40.000     0005             LTERMI=1
   41.000     0006             LTERMO=2
   42.000     0007             ITERMI=3
   43.000     0008             ITERMO=4
   44.000     0009             IIN=5
   45.000     0010             IOUT=6
   46.000     0011             IOUT2=7
   47.000     0012             IOUT3=8
   48.000     0013             JQR=1
   49.000     0014             NNN=0
   50.000     0015             IX=1
   51.000     0016             WRITE(LTERMO,202)
   52.000     0017             READ(LTERMI,101)NRUN
   53.000     0018        1000 REWIND IIN
   54.000     0019             LABEL=0
   55.000     0020             N=1
   56.000      0021                  IC=0
   57.000      0022                  IFLAG=0
   58.000      0023                  DO 44 I=1,50
   59.000      0024                  K(I)=0.0
   60.000      0025                  DU(I)=0.0
   61.000      0026                  DL(I)=0.0
   62.000      0027            44    Z(I)=0.0
   63.000                      C     ****************************************************
   64.000                      C     Main Program
   65.000                      C     ****************************************************
   66.000                      C
   67.000                      C     ****************************************************
   68.000                      C     Read and set output units
   69.000                      C
   70.000                      C           NUNIT = 0 for Imperial units
   71.000                      C                 = 1 for S.I. units
   72.000                      C
   73.000                      C     ****************************************************
   74.000                      C
   75.000                      C
   76.000      0028                  READ(IIN,500)NUNIT
   77.000      0029                  IF(NUNIT.EQ.0)CALL DATAIM(LABEL)
   78.000      0030                  IF(NUNIT.EQ.1)CALL DATASI(LABEL)
   79.000      0031                  IF(NUNIT.NE.0.AND.NUNIT.NE.1)GO TO 25
   80.000      0032                  Z(N)=H1+H2
   81.000      0033                  TSHTT=10.0*(H1+H2)
   82.000      0034                  WRITE(LTERMO,200)JQR
   83.000      0035                  READ(LTERMI,100)ITOA
   84.000      0036                  IF(ITOA.EQ.2)WRITE(IOUT,610)JQR
   85.000      0037                  IF(ITOA.EQ.1)WRITE(IOUT,611)JQR
   86.000      0038                  IF(ITOA.EQ.2)WRITE(LTERMO,203)
   87.000      0039                  IF(ITOA.EQ.2)GO TO 18
   88.000      0040                  READ(IIN,501)STBETA,STT,STC,STPHI
   89.000      0041                  STBETA=STBETA*0.01745
   90.000      0042                  STPHI=STPHI*0.01745
   91.000      0043                  WRITE(LTERMO,201)
   92.000      0044                  WRITE(IOUT,613)
   93.000      0045                  BETA=RNORMB(BETAM,STBETA,IX)
   94.000      0046                  T=RNORMT(TM,STT,IX)
   95.000      0047                  C=RNORMC(CM,STC,IX)
   96.000      0048                  PHI=RNORMP(PHIM,STPHI,IX)
   97.000      0049                  PBETAM=BETAM/0.01745
   98.000      0050                  PBETA=BETA/0.01745
   99.000      0051                  PPHIM=PHIM/0.01745
  100.000      0052                  PPHI=PHI/0.01745
  101.000      0053                  PSTBET=STBETA/0.01745
  102.000      0054                  PSTPHI=STPHI/0.01745
  103.000      0055                  WRITE(IOUT,614)
  104.000      0056                  WRITE(IOUT,615)PBETAM,PSTBET,PBETA
  105.000      0057                  WRITE(IOUT,616)TM,STT,T
  106.000      0058                  WRITE(IOUT,617)CM,STC,C
  107.000      0059                  WRITE(IOUT,618)PPHIM,PSTPHI,PPHI
  108.000      0060                  GO TO 1
  109.000      0061            18    BETA=BETAM
  110.000      0062                  T=TM
  111.000     0063              C=CM
  112.000     0064              PHI=PHIM
  113.000     0065        1     A=H1+H2-Z(N)
  114.000     0066              IF(LABEL.EQ.1)GO TO 24
  115.000     0067              X=DCOTAN(AI1)-DCOTAN(AI2)
  116.000     0068              IF(BETA.LE.O.O)GO TO 2
  117.000     0069              IF(H2*DCOTAN(BETA)-H2*DCOTAN(AI2)-XB)21,21,2
  118.000     0070        2     IA=1
  119.000     0071              IS=1
  120.000     0072              IWRITE=O
  121.000     0073              MAG=O
  122.000     0074        99    K(N+1)=IA*DELTA
  123.000     0075              Z(N+1)=Z(N)-(IA*DELTA*DTAN(BETA))
  124.000     0076              IF(IA*DELTA.GT.TSHTT)GO TO 26
  125.000     0077        5     B=H1+H2-Z(N+1)
  126.000     0078              R=A*(1.+DCOS(BETA)*DTAN(AI1))-XB*DTAN(BETA)-H2*DCOTAN(AI2)
  127.000                    &*DTAN(BETA)
  128.000     0079              ALPHA=Z(N+1)+HW-H1-H2
  129.000     0080              SUMKN=O.O
  130.000     0081              DO 6 J=1,N
  131.000     0082        6     SUMKN=SUMKN+K(J)
  132.000     0083              IF(SUMKN.GT.TSHTT)GO TO 26
  133.000     0084              IF(SUMKN)2O,7,7
  134.000     0085        7     IF(SUMKN-H2*DCOTAN(AI2))8,8,9
  135.000     0086        8     CALL CASEA(IFLAG)
  136.000     0087              IF(IFLAG.EQ.1)GO TO 22
  137.000     0088              IF(IFLAG.EQ.2)GO TO 23
  138.000     0089              IF(IC.EQ.1)GO TO 1
  139.000     0090              GO TO 99
  140.000     0091        9     IF(SUMKN-H2*DCOTAN(AI2)-XB)1O,1O,11
  141.000     0092        10    CALL CASEB(IFLAG)
  142.000     0093              IF(IFLAG.EQ.1)GO TO 22
  143.000     0094              IF(IFLAG.EQ.2)GO TO 23
  144.000     0095              IF(IC.EQ.1)GO TO 1
  145.000     0096              GO TO 99
  146.000     0097        11    IF(SUMKN-H2*DCOTAN(AI2)-XB-H1*DCOTAN(AI1))12,12,13
  147.000     0098        12    CALL CASEC(IFLAG)
  148.000     0099              IF(IFLAG.EQ.1)GO TO 22
  149.000     0100              IF(IFLAG.EQ.2)GO TO 23
  150.000     0101              IF(IC.EQ.1)GO TO 1
  151.000     0102              GO TO 99
  152.000     0103        13    IF(BETA.LE.O.O)GO TO 14
  153.000     0104              IF(SUMKN-(H1+H2)*DCOTAN(BETA))14,14,15
  154.000     0105        14    CALL CASED(IFLAG)
  155.000     0106              IF(IFLAG.EQ.1)GO TO 22
  156.000     0107              IF(IFLAG.EQ.2)GO TO 23
  157.000     0108              IF(IC.EQ.1)GO TO 1
  158.000     0109              GO TO 99
  159.000     0110        15    IF(IS.EQ.1)GO TO 16
  160.000     0111              WRITE(IOUT,602)N
  161.000     0112              Z(N)=Z(N+1)
  162.000     0113              N=N+1
  163.000     0114              GO TO 1
  164.000     0115        16    WRITE(IOUT,603)
  165.000     0116              GO TO 24
  166.000     0117         20    WRITE(IOUT,600)
  167.000     0118               GO TO 24
  168.000     0119         21    WRITE(IOUT,601)
  169.000     0120               GO TO 24
  170.000     0121         22    IF(IS.EQ.1)WRITE(IOUT,604)SF
  171.000     0122               IF(IS.EQ.2)WRITE(IOUT,602)N
  172.000     0123               GO TO 24
  173.000     0124         23    WRITE(IOUT,605)
  174.000     0125         24    WRITE(IOUT,609)JQR,NRUN
  175.000     0126               IF(JQR.EQ.1)WRITE(IOUT2,700)
  176.000     0127               IF(JQR.EQ.1)WRITE(IOUT3,800)
  177.000     0128               IF(N.EQ.1)GO TO 70
  178.000     0129               IF(N.GT.15)N=15
  179.000     0130               NB=N-1
  180.000     0131               WRITE(IOUT2,701)JQR,(DL(IUO),IUO=1,NB)
  181.000     0132               WRITE(IOUT3,801)JQR,(DU(IUO),IUO=1,NB)
  182.000     0133               GO TO 80
  183.000     0134         70    WRITE(IOUT2,702)JQR,SF
  184.000     0135               WRITE(IOUT3,802)JQR,SF
  185.000     0136         80    JQR=JQR+1
  186.000     0137               IF(JQR.LE.NRUN)GO TO 1000
  187.000     0138               WRITE(IOUT,606)
  188.000     0139               STOP
  189.000     0140         25    WRITE(IOUT,607)
  190.000     0141               GO TO 24
  191.000     0142         26    WRITE(IOUT,608)
  192.000     0143               GO TO 24
  193.000                  C     *****************************************************
  194.000                  C     Format Statements
  195.000                  C     *****************************************************
  196.000                  C
  197.000     0144        100    FORMAT(I1)
  198.000     0145        101    FORMAT(I2)
  199.000     0146        200    FORMAT(//'Type of analysis required for run #',I3,'?'//
  200.000                      1        'Option 1: Probabilistic'/
  201.000                      1        'Option 2: Deterministic'/
  202.000                      1        'Enter 1 or 2')
  203.000     0147        201    FORMAT(//'Probabilistic Analysis is to be performed'//
  204.000                      1        'Parameters to be selected randomly by'/
  205.000                      1         'MBPSSF from normal distributions')
  206.000     0148        202    FORMAT(//'Welcome to:'//20X,'MBPSSF'//
  207.000                      1        '"Multiple Block Plane Shear Slope Failure"'//
  208.000                      1        '  Developed by K. Barron and B. Stimpson'
  209.000                      1        //'How many successive program runs are required?'/
  210.000                      1        '(maximum of 99)'/
  211.000                      1        'for example: if 8 runs are required, enter 08')
  212.000     0149        203    FORMAT(//'Deterministic Analysis is to be performed')
  213.000     0150        500    FORMAT(G20.0)
  214.000     0151        501    FORMAT(4G20.0)
  215.000     0152        600    FORMAT('0',10X,'Invalid Case - Sum of Kn not greater than 0')
  216.000     0153        601    FORMAT('0',10X,'Treat as Two Separate Slopes')
  217.000     0154        602    FORMAT('0',10X,'Solution 2 not Obtained For Crack Number',I4)
  218.000     0155        603    FORMAT('0',10X,'SLOPE ANALYSIS COMPLETE')
  219.000     0156        604    FORMAT('0',10X,'Invalid Case - Kn+1 is greater than ',
  220.000                      1        '(H1+H2)cot(beta)-Acot(beta)'/' ',25X,
  221.000                        1       'Factor of Safety (of remaining wedge) =',F8.4)
  222.000     0157          605  FORMAT('0',10X,'Invalid Case - Kn+1 less than 0')
  223.000     0158          606  FORMAT('0',10X,'Finish'/'0',10X,'Good - Bye')
  224.000     0159          607  FORMAT('0',10X,'*** ERROR *** Output units not specified')
  225.000     0160          608  FORMAT('0',10X,'Program Run Terminated'/' ',10X,
  226.000                        1      'Distance from toe of slope to last crack exceeds ',
  227.000                        1      '10 x total slope height')
  228.000     0161          609  FORMAT('0',10X,'Completion of run # ',I2,' (Total of ',I2,
  229.000                        1       ' runs were requested)')
  230.000     0162          610  FORMAT('0',9X,87('*')/10X,'Run #',I3,5X,
  231.000                        1       'Type of Analysis: Deterministic (option 2)'/
  232.000                        1       10X,87('*'))
  233.000     0163          611  FORMAT('0',9X,87('*')/10X,'Run #',I3,5X,
  234.000                        1       'Type of Analysis: Probabilistic (option 1)'/
  235.000                        1       10X,87('*'))
  236.000     0164          613  FORMAT('0',10X,'The set of parameters to be used in this run',
  237.000                        1       ' will be selected by MBPSSF.'/10X,'The selection',
  238.000                        1       ' will be made randomly from normal distributions')
  239.000     0165          614  FORMAT('0',10X,'Parameter',5X,'Mean Value',5X,
  240.000                        1       'Standard Deviation',5X,'Value Generated from Normal',
  241.000                        1       ' Distribution'/11X,9('_'),5X,10('_'),5X,
  242.000                        1       18('_'),5X,40('_'))
  243.000     0166          615  FORMAT('0',10X,'   Beta ',5X,F10.2,12X,F7.3,29X,F10.2)
  244.000     0167          616  FORMAT(' ',15X,'T',8X,F10.3,11X,F7.3,30X,F10.3)
  245.000     0168          617  FORMAT(' ',15X,'C',8X,F10.3,11X,F7.3,30X,F10.3)
  246.000     0169          618  FORMAT(' ',15X,'Phi',5X,F10.2,12X,F7.3,29X,F10.2)
  247.000     0170          700  FORMAT('-',60X,'Summary (lower limit)'//56X,
  248.000                        1       '   Distance to crack number'
  249.000                        1      /21X,'1',7X,'2',7X,'3',7X,'4',7X,'5',7X,'6',7X,'7',
  250.000                        1       7X,'8',7X,'9',6X,'10',6X,'11',6X,'12',6X,'13',6X,'14')
  251.000     0171          800  FORMAT('-',60X,'Summary (upper limit)'//56X,
  252.000                        1       '   Distance to crack number'
  253.000                        1      /21X,'1',7X,'2',7X,'3',7X,'4',7X,'5',7X,'6',7X,'7',
  254.000                        1       7X,'8',7X,'9',6X,'10',6X,'11',6X,'12',6X,'13',6X,'14')
  255.000     0172          701  FORMAT(' ',10X,'Run',I3,20F8.3)
  256.000     0173          801  FORMAT(' ',10X,'Run',I3,20F8.3)
  257.000     0174          702  FORMAT(' ',10X,'Run',I3,'   No Solution found -',
  258.000                        1       ' Factor of safety = ',F8.3)
  259.000     0175          802  FORMAT(' ',10X,'Run',I3,'   No Solution found -',
  260.000                        1       ' Factor of safety = ',F8.3)
  261.000     0176               END
  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = MAIN    , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       176,PROGRAM SIZE =     6904

  *STATISTICS*  NO DIAGNOSTICS GENERATED
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MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        DATAIM       07-29-84     15:56:41          PAGE 0001

  262.000     0001                SUBROUTINE DATAIM(LABEL)
  263.000     0002                IMPLICIT REAL*8(A-H,K,O-Z)
  264.000                 C       * * * * * * * * * * * * * * * * * * * *
  265.000                 C       *  READ INPUT DATA (Imperial Units)    *
  266.000                 C       * * * * * * * * * * * * * * * * * * * *
  267.000                 C
  268.000                 C
  269.000                 C       ************************************************************
  270.000                 C       Argument -
  271.000                 C
  272.000                 C       LABEL - End of File Indicator
  273.000                 C               = 0  If execution is to continue
  274.000                 C               = 1  If execution is to terminate
  275.000                 C
  276.000                 C       ***********************************************************
  277.000                 C
  278.000                 C       ***********************************************************
  279.000                 C       Dimensions
  280.000                 C       ***********************************************************
  281.000                 C
  282.000     0003                COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
  283.000                        *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
  284.000                        *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
  285.000                        *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
  286.000                 C
  287.000     0004                DIMENSION TITLE(20)
  288.000                 C
  289.000                 C       ***********************************************************
  290.000                 C       Heading
  291.000                 C       ***********************************************************
  292.000                 C
  293.000     0005                WRITE(IOUT,600)
  294.000     0006                IF(JQR.EQ.1)WRITE(IOUT2,600)
  295.000     0007                IF(JQR.EQ.1)WRITE(IOUT3,600)
  296.000                 C
  297.000                 C       ***********************************************************
  298.000                 C       Problem Indentification
  299.000                 C       ***********************************************************
  300.000                 C
  301.000     0008                READ (IIN,501,END=99)(TITLE(I),I=1,20)
  302.000     0009                WRITE(IOUT,601)(TITLE(I),I=1,20)
  303.000     0010                IF(JQR.EQ.1)WRITE(IOUT2,601)(TITLE(I),I=1,20)
  304.000     0011                IF(JQR.EQ.1)WRITE(IOUT3,601)(TITLE(I),I=1,20)
  305.000                 C
  306.000                 C
  307.000                 C       ***********************************************************
  308.000                 C       Geometric Data and Material Properties
  309.000                 C       ***********************************************************
  310.000                 C
  311.000     0012                READ(IIN,502)H1,H2,HW,XB
  312.000     0013                READ(IIN,503)AI1,AI2,BETAM
  313.000     0014                READ(IIN,504)DELTA
  314.000     0015                READ(IIN,505)TM,CM,GAMMA,GAMMAW,PHIM
  315.000     0016                WRITE(IOUT,602)
  316.000     0017                WRITE(IOUT,603)H1,H2,HW,XB,AI1,AI2,BETAM,DELTA
  317.000     0018                 WRITE(IOUT,604)
  318.000     0019                 WRITE(IOUT,605)TM,CM,GAMMA,GAMMAW,PHIM
  319.000                    C
  320.000                    C     *******************************************************
  321.000                    C     Convert angles from degrees to radians
  322.000                    C     *******************************************************
  323.000                    C
  324.000     0020                 RAD=0.01745
  325.000     0021                 AI1=AI1*RAD
  326.000     0022                 AI2=AI2*RAD
  327.000     0023                 BETAM=BETAM*RAD
  328.000     0024                 PHIM=PHIM*RAD
  329.000                    C
  330.000     0025                 LABEL=0
  331.000     0026                 RETURN
  332.000     0027           99    LABEL=1
  333.000     0028                 RETURN
  334.000                    C     ********************************************************
  335.000                    C     Format Statements
  336.000                    C     ********************************************************
  337.000                    C
  338.000     0029          501    FORMAT(20A4)
  339.000     0030          502    FORMAT(4G20.0)
  340.000     0031          503    FORMAT(3G20.0)
  341.000     0032          504    FORMAT(G20.0)
  342.000     0033          505    FORMAT(5G20.0)
  343.000     0034          600    FORMAT('1',37X,55('*')/' ',37X,'*',53X,'*'/
  344.000                         1        ' ',37X,'*',23X,'MBPSSF',24X'*'/
  345.000                         1        ' ',37X,'*',6X,'Multiple Block Plane Shear Slope Failure',
  346.000                         1        7X,'*'/' ',37X'*',53X,'*'/' ',37X,55('*'))
  347.000     0035          601    FORMAT('-',10X,20A4)
  348.000     0036          602    FORMAT('-',10X,'Geometric Data')
  349.000     0037          603    FORMAT(' ',25X,'Height of the upper slope',28('.'),'(H1)',
  350.000                         1        2X,'=',F10.2,' ft'/
  351.000                         1        ' ',25X,'Height of the lower slope',28('.'),'(H2)',
  352.000                         1        2X,'=',F10.2,' ft'/
  353.000                         1        ' ',25X,'Height of the water table',28('.'),'(Hw)',
  354.000                         1        2X,'=',F10.2,' ft'/
  355.000                         1        ' ',25X,'Bench width',42('.'),'(Xb)',2X,'=',F10.2,' ft'/
  356.000                         1        ' ',25X,'Angle of the upper slope with the horizontal',
  357.000                         1        8('.'),'(A11)',2X,'=',F10.2,' deg'/
  358.000                         1        ' ',25X,'Angle of the lower slope with the horizontal',
  359.000                         1        8('.'),'(A12)',2X,'=',F10.2,' deg'/
  360.000                         1        ' ',25X,'Angle of the failure plane with the horizontal',
  361.000                         1        5('.'),'(Beta)',2X,'=',F10.2,' deg'/
  362.000                         1        ' ',25X,'Incremental horizontal distance',19('.'),
  363.000                         1        '(Delta)',2X,'=',F10.4,' ft'/)
  364.000     0038          604    FORMAT('-',10X,'Material Properties')
  365.000     0039          605    FORMAT(' ',25X,'Tensile strength of the rock',26('.'),
  366.000                         1        '(T)',2X,'=',F10.3,' psf'/
  367.000                         1        ' ',25X,'Effective cohesion on the failure surface',
  368.000                         1        13('.'),'(C)',2X,'=',F10.3,' psf'/
  369.000                         1        ' ',25X,'Density of rock in the failed wedge',
  370.000                         1        15('.'),'(Gamma)',2X,'=',F10.3,' pcf'/
  371.000                         1        ' ',25X,'Density of water',33('.'),
  372.000                      1       '(Gammaw)',2X,'=',F10.3,' pcf'/
  373.000                      1       ' ',25X,'Effective angle of friction on the failure plane',
  374.000                      1       4('.'),'(Phi)',2X,'=',F10.3,' deg'//)
  375.000    0040               END
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MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        DATAIM      07-29-84     15:56:41         PAGE 0004

  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = DATAIM  , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       40,PROGRAM SIZE =     2472

  *STATISTICS*  NO DIAGNOSTICS GENERATED
  376.000     0001                SUBROUTINE DATASI(LABEL)
  377.000     0002                IMPLICIT REAL*8(A-H,K,O-Z)
  378.000               C         * * * * * * * * * * * * * * * * * * *
  379.000               C         *  READ INPUT DATA (S.I. units)    *
  380.000               C         * * * * * * * * * * * * * * * * * * *
  381.000               C
  382.000               C
  383.000               C         ************************************************************
  384.000               C         Argument -
  385.000               C
  386.000               C         LABEL - End of File Indicator
  387.000               C                 = 0  If execution is to continue
  388.000               C                 = 1  If execution is to terminate
  389.000               C
  390.000               C         ***********************************************************
  391.000               C
  392.000               C         ***********************************************************
  393.000               C         Dimensions
  394.000               C         ***********************************************************
  395.000               C
  396.000     0003                COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
  397.000                        *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
  398.000                        *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
  399.000                        *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
  400.000               C
  401.000     0004                DIMENSION TITLE(20)
  402.000               C
  403.000               C         ***********************************************************
  404.000               C         Heading
  405.000               C         ***********************************************************
  406.000               C
  407.000     0005                WRITE(IOUT,600)
  408.000     0006                IF(JQR.EQ.1)WRITE(IOUT2,600)
  409.000     0007                IF(JQR.EQ.1)WRITE(IOUT3,600)
  410.000               C
  411.000               C         ***********************************************************
  412.000               C         Problem Indentification
  413.000               C         ***********************************************************
  414.000               C
  415.000     0008                READ (IIN,501,END=99)(TITLE(I),I=1,20)
  416.000     0009                WRITE(IOUT,601)(TITLE(I),I=1,20)
  417.000     0010                IF(JQR.EQ.1)WRITE(IOUT2,601)(TITLE(I),I=1,20)
  418.000     0011                IF(JQR.EQ.1)WRITE(IOUT3,601)(TITLE(I),I=1,20)
  419.000               C
  420.000               C
  421.000               C         ***********************************************************
  422.000               C         Geometric Data and Material Properties
  423.000               C         ***********************************************************
  424.000               C
  425.000     0012                READ(IIN,502)H1,H2,HW,XB
  426.000     0013                READ(IIN,503)AI1,AI2,BETAM
  427.000     0014                READ(IIN,504)DELTA
  428.000     0015                READ(IIN,505)TM,CM,GAMMA,GAMMAW,PHIM
  429.000     0016                WRITE(IOUT,602)
  430.000     0017                WRITE(IOUT,603)H1,H2,HW,XB,AI1,AI2,BETAM,DELTA
  431.000    0018             WRITE(IOUT,604)
  432.000    0019             WRITE(IOUT,605)TM,CM,GAMMA,GAMMAW,PHIM
  433.000              C
  434.000              C      ******************************************************
  435.000              C      Convert angles from degrees to radians
  436.000              C      ******************************************************
  437.000              C
  438.000    0020             RAD=0.01745
  439.000    0021             AI1=AI1*RAD
  440.000    0022             AI2=AI2*RAD
  441.000    0023             BETAM=BETAM*RAD
  442.000    0024             PHIM=PHIM*RAD
  443.000              C
  444.000    0025             LABEL=0
  445.000    0026             RETURN
  446.000    0027      99     LABEL=1
  447.000    0028             RETURN
  448.000              C      ******************************************************
  449.000              C      Format Statements
  450.000              C      ******************************************************
  451.000              C
  452.000    0029      501    FORMAT(20A4)
  453.000    0030      502    FORMAT(4G20.0)
  454.000    0031      503    FORMAT(3G20.0)
  455.000    0032      504    FORMAT(G20.0)
  456.000    0033      505    FORMAT(5G20.0)
  457.000    0034      600    FORMAT('1',37X,55('*')/' ',37X,'*',53X,'*'/
  458.000                  1          ' ',37X,'*',23X,'MBPSSF',24X'*'/
  459.000                  1          ' ',37X,'*',6X,'Multiple Block Plane Shear Slope Failure',
  460.000                  1          7X,'*'/' ',37X'*',53X,'*'/' ',37X,55('*'))
  461.000    0035      601    FORMAT('-',10X,20A4)
  462.000    0036      602    FORMAT('-',10X,'Geometric Data')
  463.000    0037      603    FORMAT(' ',25X,'Height of the upper slope',28('.'),'(H1)',
  464.000                  1          2X,'=',F10.2,' m'/
  465.000                  1          ' ',25X,'Height of the lower slope',28('.'),'(H2)',
  466.000                  1          2X,'=',F10.2,' m'/
  467.000                  1          ' ',25X,'Height of the water table',28('.'),'(Hw)',
  468.000                  1          2X,'=',F10.2,' m'/
  469.000                  1          ' ',25X,'Bench width',42('.'),'(Xb)',2X,'=',F10.2,' m'/
  470.000                  1          ' ',25X,'Angle of the upper slope with the horizontal',
  471.000                  1          8('.'),'(AI1)',2X,'=',F10.2,' deg'/
  472.000                  1          ' ',25X,'Angle of the lower slope with the horizontal',
  473.000                  1          8('.'),'(AI2)',2X,'=',F10.2,' deg'/
  474.000                  1          ' ',25X,'Angle of the failure plane with the horizontal',
  475.000                  1          5('.'),'(Beta)',2X,'=',F10.2,' deg'/
  476.000                  1          ' ',25X,'Incremental horizontal distance',19('.'),
  477.000                  1          '(Delta)',2X,'=',F10.4,' m'/)
  478.000    0038      604    FORMAT('-',10X,'Material Properties')
  479.000    0039      605    FORMAT(' ',25X,'Tensile strength of the rock',26('.'),
  480.000                  1          '(T)',2X,'=',F10.3,' kPa'/
  481.000                  1          ' ',25X,'Effective cohesion on the failure surface',
  482.000                  1          13('.'),'(C)',2X,'=',F10.3,' kPa'/
  483.000                  1          ' ',25X,'Density of rock in the failed wedge',
  484.000                  1          15('.'),'(Gamma)',2X,'=',F10.3,' kN/m3'/
  485.000                  1          ' ',25X,'Density of water',33('.'),
  486.000                    1       '(Gammaw)',2X,'=',F10.3,' kN/m3'/
  487.000                    1       ' ',25X,'Effective angle of friction on the failure plane',
  488.000                    1       4('.'),'(Phi)',2X,'=',F10.3,' deg'//)
  489.000    0040             END
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MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        DATASI      07-29-84     15:56:42        PAGE 0004

  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = DATASI   , LINECNT =        57

  *STATISTICS*    SOURCE STATEMENTS =        40,PROGRAM SIZE =      2472

  *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
          SUBROUTINE CASEA(IFLAG)
          IMPLICIT REAL*8(A-H,K,O-Z)
      C   * * * * * * * * * * *
      C   *    Case A         *
      C   * * * * * * * * * * *
      C
      C   *********************************************************
      C   Dimensions
      C   *********************************************************
      C
          COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
         *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
         *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
         *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
      C
      C
          IF(BETA.LE.0)GO TO 2
          IF((H1+H2)*DCOTAN(BETA)-A*DCOTAN(BETA)-K(N+1))1,1,2
      1   IFLAG=1
          RETURN
      2   IF(H2*DCOTAN(AI2)+XB+H1*DCOTAN(AI1)-A*DCOTAN(BETA)-K(N+1))3,3,4
      3   CALL SUB1
          RETURN
      4   IF(H2*DCOTAN(AI2)+XB-A*DCOTAN(BETA)-K(N+1))5,5,6
      5   CALL SUB2
          RETURN
      6   IF(H2*DCOTAN(AI2)-A*DCOTAN(BETA)-K(N+1))7,7,8
      7   CALL SUB3
          RETURN
      8   IF(K(N+1))9,10,10
      9   IFLAG=2
          RETURN
      10  CALL SUB4
          RETURN
          END
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        CASEA       07-29-84    15:56:43        PAGE 0002

  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = CASEA   , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       22,PROGRAM SIZE =      868

  *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        CASEB       07-29-84     15:56:44          PAGE 0001

   525.000     0001                SUBROUTINE CASEB(IFLAG)
   526.000     0002                IMPLICIT REAL*8(A-H,K,O-Z)
   527.000                C        * * * * * * * * * * *
   528.000                C        *     Case B          *
   528.000                C        * * * * * * * * * * *
   530.000                C
   531.000                C        ************************************************************
   532.000                C        Dimensions
   533.000                C        ************************************************************
   534.000                C
   535.000     0003                COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
   536.000                        *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
   537.000                        *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
   538.000                        *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
   539.000                C
   540.000                C
   541.000     0004                IF(BETA.LE.O)GO TO 2
   542.000     0005                IF((H1+H2)*DCOTAN(BETA)-A*DCOTAN(BETA)-K(N+1))1,1,2
   543.000     0006       1        IFLAG=1
   544.000     0007                RETURN
   545.000     0008       2        IF(H2*DCOTAN(AI2)+XB+H1*DCOTAN(AI1)-A*DCOTAN(BETA)-K(N+1))3,3,4
   546.000     0009       3        CALL SUB5
   547.000     0010                RETURN
   548.000     0011       4        IF(H2*DCOTAN(AI2)+XB-A*DCOTAN(BETA)-K(N+1))5,5,6
   549.000     0012       5        CALL SUB6
   550.000     0013                RETURN
   551.000     0014       6        IF(K(N+1))7,8,8
   552.000     0015       7        IFLAG=2
   553.000     0016                RETURN
   554.000     0017       8        CALL SUB7
   555.000     0018                RETURN
   556.000     0019                END
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        CASEB       07-29-84    15:56:44        PAGE 0002

  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = CASEB   , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       19,PROGRAM SIZE =      756

  *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        CASEC       07-29-84     15:56:44         PAGE 0001

  557.000     0001                SUBROUTINE CASEC(IFLAG)
  558.000     0002                IMPLICIT REAL*8(A-H,K,O-Z)
  559.000                  C      * * * * * * * * * * *
  560.000                  C      *    Case C         *
  561.000                  C      * * * * * * * * * * *
  562.000                  C
  563.000                  C      ***************************************************
  564.000                  C      Dimensions
  565.000                  C      ***************************************************
  566.000                  C
  567.000     0003                COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
  568.000                        *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
  569.000                        *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
  570.000                        *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
  571.000                  C
  572.000                  C
  573.000     0004                IF(BETA.LE.O)GO TO 2
  574.000     0005                IF((H1+H2)*DCOTAN(BETA)-A*DCOTAN(BETA)-K(N+1))1,1,2
  575.000     0006         1      IFLAG=1
  576.000     0007                RETURN
  577.000     0008         2      IF(H2*DCOTAN(AI2)+XB+H1*DCOTAN(AI1)-A*DCOTAN(BETA)-K(N+1))3,3,4
  578.000     0009         3      CALL SUB8
  579.000     0010                RETURN
  580.000     0011         4      IF(K(N+1))5,6,6
  581.000     0012         5      IFLAG=2
  582.000     0013                RETURN
  583.000     0014         6      CALL SUB9
  584.000     0015                RETURN
  585.000     0016                END
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        CASEC       07-29-84    15:56:44        PAGE 0002

  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = CASEC   , LINECNT =        57

  *STATISTICS*    SOURCE STATEMENTS =       16,PROGRAM SIZE =       648

  *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        CASED        07-29-84     15:56:45          PAGE 0001

  586.000     0001                  SUBROUTINE CASED(IFLAG)
  587.000     0002                  IMPLICIT REAL*8(A-H,K,O-Z)
  588.000                   C       * * * * * * * * * * *
  589.000                   C       *     Case D        *
  590.000                   C       * * * * * * * * * * *
  591.000                   C
  592.000                   C       *****************************************************
  593.000                   C       Dimensions
  594.000                   C       *****************************************************
  595.000                   C
  596.000     0003                  COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
  597.000                          *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
  598.000                          *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
  599.000                          *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
  600.000                   C
  601.000                   C
  602.000     0004                  IF(BETA.LE.0)GO TO 2
  603.000     0005                  IF((H1+H2)*DCOTAN(BETA)-A*DCOTAN(BETA)-K(N+1))1,1,2
  604.000     0006          1       IFLAG=1
  605.000     0007                  RETURN
  606.000     0008          2       IF(K(N+1))3,4,4
  607.000     0009          3       IFLAG=2
  608.000     0010                  RETURN
  609.000     0011          4       CALL SUB10
  610.000     0012                  RETURN
  611.000     0013                  END
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        CASED       07-29-84    15:56:45        PAGE 0002

  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = CASED   , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       13,PROGRAM SIZE =      510

  *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        SUB1        07-29-84     15:56:46        PAGE 0001

  612.000     0001                  SUBROUTINE SUB1
  613.000     0002                  IMPLICIT REAL*8(A-H,K,O-Z)
  614.000              C            * * * * * * * * * * * *
  615.000              C            *    Case A1          *
  616.000              C            * * * * * * * * * * * *
  617.000              C
  618.000              C            ***********************************************************
  619.000              C            Dimensions
  620.000              C            ***********************************************************
  621.000              C
  622.000     0003                  COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
  623.000                          *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
  624.000                          *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
  625.000                          *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
  626.000              C
  627.000              C
  628.000     0004                  W=GAMMA/2.*(DCOTAN(BETA)*((H1+H2)**2-Z(N+1)**2)
  629.000                          &    +A**2*DCOTAN(BETA)*(1.-DCOTAN(BETA)*DTAN(AI2))
  630.000                          &    -DCOTAN(AI2)*(H1+H2)**2-H1**2*(DCOTAN(AI1)-DCOTAN(AI2))
  631.000                          &    -2.*H1*XB)
  632.000     0005                  P0=0.0
  633.000     0006                  P1=GAMMAW*H2*(1.-DCOTAN(AI2)*DTAN(BETA))
  634.000     0007                  P2=GAMMAW*(H2*(1.-DCOTAN(AI2)*DTAN(BETA))-XB*DTAN(BETA))
  635.000     0008                  P3=GAMMAW*(HW+DTAN(BETA)*(H2*(DCOTAN(AI1)-DCOTAN(AI2))
  636.000                          &    -HW*DCOTAN(AI1)-XB))
  637.000     0009                  P4=GAMMAW*ALPHA
  638.000     0010                  AT=1./DSIN(BETA)*(B-A)
  639.000     0011                  A1=1./DSIN(BETA)*(H2*DCOTAN(AI2)*DTAN(BETA)-A)
  640.000     0012                  A2=1./DSIN(BETA)*(XB*DTAN(BETA))
  641.000     0013                  A3=1./DSIN(BETA)*((HW-H2)*DCOTAN(AI1)*DTAN(BETA))
  642.000     0014                  A4=1./DSIN(BETA)*(B+DTAN(BETA)*(H2*X-HW*DCOTAN(AI1)-XB))
  643.000     0015                  IF(B-HW)1,2,2
  644.000     0016             1    IFLOG=1
  645.000     0017                  GO TO 7
  646.000     0018             2    IF(H2-HW)3,4,4
  647.000     0019             3    IFLOG=2
  648.000     0020                  P4=0.0
  649.000     0021                  A4=1./DSIN(BETA)*(B+DTAN(BETA)*(H2*X-HW*DCOTAN(AI1)-XB)-ALPHA)
  650.000     0022                  V=0.0
  651.000     0023                  GO TO 8
  652.000     0024             4    IF(A*DCOTAN(BETA)*DTAN(AI2)-HW)5,6,6
  653.000     0025             5    IFLOG=3
  654.000     0026                  P2=0.0
  655.000     0027                  P3=0.0
  656.000     0028                  P4=0.0
  657.000     0029                  A2=1./DSIN(BETA)*(HW*(1.-DCOTAN(AI2)*DTAN(BETA)))
  658.000     0030                  V=0.0
  659.000     0031                  GO TO 8
  660.000     0032             6    IFLOG=4
  661.000     0033                  V=0.0
  662.000     0034                  U=0.0
  663.000     0035                  GO TO 9
  664.000     0036             7    V=GAMMAW*ALPHA**2/2.
  665.000     0037             8    U=1./2.*((P3+P4)*A4+(P2+P3)*A3+(P2+P1)*A2+(P1+P0)*A1)
  666.000     0038             9    Y=T*Z(N+1)
  667.000     0039               IF(NUNIT)99,99,100
  668.000     0040        99     CALL SUB11I
  669.000     0041               GO TO 101
  670.000     0042       100     CALL SUB11S
  671.000     0043       101     IF(SF.LT.0.99.OR.SF.GT.1.01)GO TO 10
  672.000     0044               IF(NUG.EQ.0)GO TO 10
  673.000     0045               AREST=A*DCOTAN(BETA)*DTAN(AI2)
  674.000     0046               IF(IFLOG.EQ.1)WRITE(IOUT,600)HW,B
  675.000     0047               IF(IFLOG.EQ.2)WRITE(IOUT,601)HW,H2
  676.000     0048               IF(IFLOG.EQ.3)WRITE(IOUT,602)HW,AREST
  677.000     0049               IF(IFLOG.EQ.4)WRITE(IOUT,603)HW,AREST
  678.000     0050        10     RETURN
  679.000                C       **********************************************************
  680.000                C       Format Statements
  681.000                C       **********************************************************
  682.000                C
  683.000     0051       600     FORMAT(' ',12X,'Case A1(a) - HW > B ie.',F7.2,' > ',F7.2)
  684.000     0052       601     FORMAT(' ',12X,'Case A1(b) - HW > H2 ie.',F7.2,' > ',F7.2)
  685.000     0053       602     FORMAT(' ',12X,'Case A1(c) - HW > A * cot(BETA) * tan(i2) ie.',
  686.000                     1         F7.2,' > ',F7.2)
  687.000     0054       603     FORMAT(' ',12X,'Case A1(d) - HW < A * cot(BETA) * tan(i2) ie.',
  688.000                     1         F7.2,' < ',F7.2)
  689.000     0055               END
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        SUB1        07-29-84    15:56:46        PAGE 0003

  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = SUB1    , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       55,PROGRAM SIZE =     2600

  *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
 690.000     0001                 SUBROUTINE SUB2
 691.000     0002                 IMPLICIT REAL*8(A-H,K,O-Z)
 692.000                    C     * * * * * * * * * * *
 693.000                    C     *    Case A2         *
 694.000                    C     * * * * * * * * * * *
 695.000                    C
 696.000                    C     ***************************************************
 697.000                    C     Dimensions
 698.000                    C     ***************************************************
 699.000                    C
 700.000     0003                 COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
 701.000                         *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
 702.000                         *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
 703.000                         *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
 704.000                    C
 705.000                    C
 706.000     0004                 SAVEHW=HW
 707.000     0005                 SS=H2*(1.-DCOTAN(AI2)*DTAN(AI1))+B*DCOTAN(BETA)*DTAN(AI1)
 708.000                         &    -XB*DTAN(AI1)
 709.000     0006                 IF(HW.GT.SS)HW=SS
 710.000     0007                 W=GAMMA/2.*(DCOTAN(BETA)*((H1+H2)**2-Z(N+1)**2)
 711.000                         &    +A**2*DCOTAN(BETA)*(1.-DCOTAN(BETA)*DTAN(AI2))
 712.000                         &    -DCOTAN(AI2)*(H1+H2)**2-H1**2*(DCOTAN(AI1)-DCOTAN(AI2))
 713.000                         &    -2*H1*XB-DTAN(AI1)*(H2*DCOTAN(AI2)+XB+H1*DCOTAN(AI1)
 714.000                         &    -B*DCOTAN(BETA))**2)
 715.000     0008                 P0=0.0
 716.000     0009                 P1=GAMMAW*H2*(1.-DCOTAN(AI2)*DTAN(BETA))
 717.000     0010                 P2=GAMMAW*(H2*(1.-DCOTAN(AI2)*DTAN(BETA))-XB*DTAN(BETA))
 718.000     0011                 P3=GAMMAW*(HW+DTAN(BETA)*(H2*(DCOTAN(AI1)-DCOTAN(AI2))
 719.000                         &    -HW*DCOTAN(AI1)-XB))
 720.000     0012                 P4=GAMMAW*ALPHA
 721.000     0013                 AT=1./DSIN(BETA)*(B-A)
 722.000     0014                 A1=1./DSIN(BETA)*(H2*DCOTAN(AI2)*DTAN(BETA)-A)
 723.000     0015                 A2=1./DSIN(BETA)*(XB*DTAN(BETA))
 724.000     0016                 A3=1./DSIN(BETA)*((HW-H2)*DCOTAN(AI1)*DTAN(BETA))
 725.000     0017                 A4=1./DSIN(BETA)*(B+DTAN(BETA)*(H2*X-HW*DCOTAN(AI1)-XB))
 726.000     0018                 IF(B-HW)1,2,2
 727.000     0019           1     IFLOG=1
 728.000     0020                 GO TO 7
 729.000     0021           2     IF(H2-HW)3,4,4
 730.000     0022           3     IFLOG=2
 731.000     0023                 P4=0.0
 732.000     0024                 A4=1./DSIN(BETA)*(DTAN(BETA)*(H2*X-HW*DCOTAN(AI1)-XB)+HW)
 733.000     0025                 V=0.0
 734.000     0026                 GO TO 8
 735.000     0027           4     IF(A*DCOTAN(BETA)*DTAN(AI2)-HW)5,6,6
 736.000     0028           5     IFLOG=3
 737.000     0029                 P2=0.0
 738.000     0030                 P3=0.0
 739.000     0031                 P4=0.0
 740.000     0032                 A2=1./DSIN(BETA)*(HW*(1.-DCOTAN(AI2)*DTAN(BETA)))
 741.000     0033                 V=0.0
 742.000     0034                 GO TO 8
 743.000     0035           6     IFLOG=4
 744.000     0036                 V=0.0
```

```
          U=0.0
          GO TO 9
    7     V=GAMMAW*ALPHA**2/2.
    8     U=1./2.*((P3+P4)*A4+(P2+P3)*A3+(P2+P1)*A2+(P1+P0)*A1)
    9     Y=T*(Z(N+1)*(1.+DCOTAN(BETA)*DTAN(AI1))-H1*(1.+DCOTAN(BETA)
         &   *DTAN(AI1))-H2*DTAN(AI1)*(DCOTAN(BETA)+DCOTAN(AI2))
         &   -XB*DTAN(AI1))
          IF(NUNIT)99,99,100
    99    CALL SUB11I
          GO TO 101
    100   CALL SUB11S
    101   IF(SF.LT.0.99.OR.SF.GT.1.01)GO TO 10
          IF(NUG.EQ.0)GO TO 10
          AREST=A*DCOTAN(BETA)*DTAN(AI2)
          IF(IFLOG.EQ.1)WRITE(IOUT,600)HW,B
          IF(IFLOG.EQ.2)WRITE(IOUT,601)HW,H2
          IF(IFLOG.EQ.3)WRITE(IOUT,602)HW,AREST
          IF(IFLOG.EQ.4)WRITE(IOUT,603)HW,AREST
    10    HW=SAVEHW
          RETURN
    C     ********************************************************
    C     Format Statements
    C     ********************************************************
    C
    600   FORMAT(' ',12X,'Case A2(a) - HW > B ie.',F7.2,' > ',F7.2)
    601   FORMAT(' ',12X,'Case A2(b) - HW > H2 ie.',F7.2,' > ',F7.2)
    602   FORMAT(' ',12X,'Case A2(c) - HW > A * cot(BETA) * tan(i2) ie.',
         1        F7.2,' > ',F7.2)
    603   FORMAT(' ',12X,'Case A2(d) - HW < A * cot(BETA) * tan(i2) ie.',
         1        F7.2,' > ',F7.2)
          END
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        SUB2        07-29-84    15:56:46        PAGE 0003

  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = SUB2    , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       59,PROGRAM SIZE =     3116

  *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
              SUBROUTINE SUB3
              IMPLICIT REAL*8(A-H,K,O-Z)
        C     * * * * * * * * * * *
        C     *    Case A3        *
        C     * * * * * * * * * * *
        C
        C     ********************************************************
        C     Dimensions
        C     ********************************************************
        C
              COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
             *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
             *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
             *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
        C
        C
              SAVEHW=HW
              IF(HW.GT.H2)HW=H2
              W=GAMMA/2.*(H2**2*(DCOTAN(BETA)-DCOTAN(AI2))
             &  +A**2*DCOTAN(BETA)*(1.-DCOTAN(BETA)*DTAN(AI2))
             &  -(H2-B)**2*DCOTAN(BETA))
              P0=0.0
              P1=GAMMAW*HW*(1.-DCOTAN(AI2)*DTAN(BETA))
              P2=GAMMAW*ALPHA
              P3=0.0
              P4=0.0
              AT=1./DSIN(BETA)*(B-A)
              A1=1./DSIN(BETA)*(HW*DCOTAN(AI2)*DTAN(BETA)-A)
              A2=1./DSIN(BETA)*(B-HW*DCOTAN(AI2)*DTAN(BETA))
              IF(B-HW)1,2,2
        1     IFLOG=1
              GO TO 5
        2     IF(A*DCOTAN(BETA)*DTAN(AI2)-HW)3,4,4
        3     IFLOG=2
              P2=0.0
              A1=1./DSIN(BETA)*(B*DCOTAN(AI2)*DTAN(BETA)-A)
              A2=1./DSIN(BETA)*(HW*(1.-DCOTAN(AI2)*DTAN(BETA)))
              V=0.0
              GO TO 6
        4     IFLOG=3
              V=0.0
              U=0.0
              GO TO 7
        5     V=GAMMAW*ALPHA**2/2.
        6     U=0.5*((P1+P0)*A1+(P1+P2)*A2)
        7     Y=T*(Z(N+1)-H1)
              IF(NUNIT)99,99,100
        99    CALL SUB11I
              GO TO 101
        100   CALL SUB11S
        101   IF(SF.LT.0.99.OR.SF.GT.1.01)GO TO 10
              IF(NUG.EQ.0)GO TO' 10
              AREST=A*DCOTAN(BETA)*DTAN(AI2)
              IF(IFLOG.EQ.1)WRITE(IOUT,600)HW,B
              IF(IFLOG.EQ.2)WRITE(IOUT,601)HW,AREST
```

```
  831.000     0041                 IF(IFLOG.EQ.3)WRITE(IOUT,602)HW,AREST
  832.000     0042          10     HW=SAVEHW
  833.000     0043                 RETURN
  834.000                  C       **********************************************************
  835.000                  C       Format Statements
  836.000                  C       **********************************************************
  837.000                  C
  838.000     0044         600     FORMAT(' ',12X,'Case A3(a) - HW > B ie.',F7.2,' > ',F7.2)
  839.000     0045         601     FORMAT(' ',12X,'Case A3(b) - HW > A * cot(BETA) * tan(i2) ie.',
  840.000                 1              F7.2,' > ',F7.2)
  841.000     0046         602     FORMAT(' ',12X,'Case A3(c) - HW < A * cot(BETA) * tan(i2) ie.',
  842.000                 1              F7.2,' > ',F7.2)
  843.000     0047                 END
```

```
*OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP
*OPTIONS IN EFFECT*  NAME = SUB3    , LINECNT =       57
*STATISTICS*    SOURCE STATEMENTS =       47,PROGRAM SIZE =     2020
*STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
  844.000     0001               SUBROUTINE SUB4
  845.000     0002               IMPLICIT REAL*8(A-H,K,O-Z)
  846.000                C       * * * * * * * * * * * *
  847.000                C       *    Case A4          *
  848.000                C       * * * * * * * * * * * *
  849.000                C
  850.000                C       **********************************************************
  851.000                C       Dimensions
  852.000                C       **********************************************************
  853.000                C
  854.000     0003               COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
  855.000                       *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
  856.000                       *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
  857.000                       *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
  858.000                C
  859.000                C
  860.000     0004               SAVEHW=HW
  861.000     0005               SS=B*DCOTAN(BETA)*DTAN(AI2)
  862.000     0006               IF(HW.GT.SS)HW=SS
  863.000     0007               W=GAMMA/2.*DCOTAN(BETA)*((DCOTAN(BETA)*DTAN(AI2)-1.)
  864.000                       &  *(B**2-A**2))
  865.000     0008               P0=0.0
  866.000     0009               P1=GAMMAW*HW*(1.-DCOTAN(AI2)*DTAN(BETA))
  867.000     0010               P2=GAMMAW*ALPHA
  868.000     0011               P3=0.0
  869.000     0012               P4=0.0
  870.000     0013               AT=1./DSIN(BETA)*(B-A)
  871.000     0014               A1=1./DSIN(BETA)*(HW*DCOTAN(AI2)*DTAN(BETA)-A)
  872.000     0015               A2=1./DSIN(BETA)*(B-HW*DCOTAN(AI2)*DTAN(BETA))
  873.000     0016               IF(B-HW)1,2,2
  874.000     0017           1   IFLOG=1
  875.000     0018               GO TO 5
  876.000     0019           2   IF(A*DCOTAN(BETA)*DTAN(AI2)-HW)3,4,4
  877.000     0020           3   IFLOG=2
  878.000     0021               P2=0.0
  879.000     0022               A2=1./DSIN(BETA)*(HW*(1.-DCOTAN(AI2)*DTAN(BETA)))
  880.000     0023               V=0.0
  881.000     0024               GO TO 6
  882.000     0025           4   IFLOG=3
  883.000     0026               V=0.0
  884.000     0027               U=0.0
  885.000     0028               GO TO 7
  886.000     0029           5   V=GAMMAW*ALPHA**2/2.
  887.000     0030           6   U=0.5*((P1+P0)*A1+(P1+P2)*A2)
  888.000     0031           7   Y=T*(Z(N+1)-H1-H2+B*DCOTAN(BETA)*DTAN(AI2))
  889.000     0032               IF(NUNIT)99,99,100
  890.000     0033          99   CALL SUB11I
  891.000     0034               GO TO 101
  892.000     0035         100   CALL SUB11S
  893.000     0036         101   IF(SF.LT.0.99.OR.SF.GT.1.01)GO TO 10
  894.000     0037               IF(NUG.EQ.0)GO TO 10
  895.000     0038               AREST=A*DCOTAN(BETA)*DTAN(AI2)
  896.000     0039               IF(IFLOG.EQ.1)WRITE(IOUT,600)HW,B
  897.000     0040               IF(IFLOG.EQ.2)WRITE(IOUT,601)HW,AREST
  898.000     0041               IF(IFLOG.EQ.3)WRITE(IOUT,602)HW,AREST
  899.000     0042         10    HW=SAVEHW
  900.000     0043               RETURN
  901.000                  C     *************************************************************
  902.000                  C     Format Statements
  903.000                  C     *************************************************************
  904.000                  C
  905.000     0044         600   FORMAT(' ',12X,'Case A4(a) - HW > B ie.',F7.2,' > ',F7.2)
  906.000     0045         601   FORMAT(' ',12X,'Case A4(b) - HW > A * cot(BETA) * tan(i2) ie.',
  907.000                       1        F7.2,' > ',F7.2)
  908.000     0046         602   FORMAT(' ',12X,'Case A4(c) - HW < A * cot(BETA) * tan(i2) ie.',
  909.000                       1        F7.2,' > ',F7.2)
  910.000     0047               END
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```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        SUB4        07-29-84    15:56:49        PAGE 0003

  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = SUB4    , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       47,PROGRAM SIZE =     1904

  *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        SUB5        07-29-84     15:56:50          PAGE 0001
  911.000     0001               SUBROUTINE SUB5
  912.000     0002               IMPLICIT REAL*8(A-H,K,O-Z)
  913.000              C         * * * * * * * * * * * *
  914.000              C         *    Case B1          *
  915.000              C         * * * * * * * * * * * *
  916.000              C
  917.000              C         *********************************************************
  918.000              C         Dimensions
  919.000              C         *********************************************************
  920.000              C
  921.000     0003               COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
  922.000                       *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
  923.000                       *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
  924.000                       *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
  925.000              C
  926.000              C
  927.000     0004               W=GAMMA/2.*(DCOTAN(BETA)*(Z(N)**2-Z(N+1)**2)+H1*(2.*A
  928.000                       &  *DCOTAN(BETA)-2.*H2*DCOTAN(AI2)-H1*DCOTAN(AI1)-2.*XB))
  929.000     0005               P0=0.0
  930.000     0006               P2=GAMMAW*(H2*(1.-DCOTAN(AI2)*DTAN(BETA))-XB*DTAN(BETA))
  931.000     0007               P3=GAMMAW*(HW*(1.-DCOTAN(AI1)*DTAN(BETA))+DTAN(BETA)*(H2*X-XB))
  932.000     0008               P4=GAMMAW*ALPHA
  933.000     0009               AT=1./DSIN(BETA)*(B-A)
  934.000     0010               A12=1./DSIN(BETA)*(H2*DCOTAN(AI2)*DTAN(BETA)+XB*DTAN(BETA)-A)
  935.000     0011               A3=1./DSIN(BETA)*(DCOTAN(AI1)*DTAN(BETA)*(HW-H2))
  936.000     0012               A4=1./DSIN(BETA)*(B-DTAN(BETA)*(H1*DCOTAN(AI1)+H2*DCOTAN(AI2)
  937.000                       &    +XB))
  938.000     0013               IF(B-HW)1,2,2
  939.000     0014       1       IFLOG=1
  940.000     0015               GO TO 5
  941.000     0016       2       IF(H2-HW)3,4,4
  942.000     0017       3       IFLOG=2
  943.000     0018               P4=0.0
  944.000     0019               A4=1./DSIN(BETA)*(DTAN(BETA)*(H2*X-HW*DCOTAN(AI1)-XB)+HW)
  945.000     0020               V=0.0
  946.000     0021               GO TO 6
  947.000     0022       4       IFLOG=3
  948.000     0023               V=0.0
  949.000     0024               U=0.0
  950.000     0025               GO TO 7
  951.000     0026       5       V=GAMMAW*ALPHA**2/2.
  952.000     0027       6       U=0.5*((A12)*(P0+P2)+A3*(P2+P3)+A4*(P3+P4))
  953.000     0028       7       Y=T*Z(N+1)
  954.000     0029               IF(NUNIT)99,99,100
  955.000     0030       99      CALL SUB11I
  956.000     0031               GO TO 101
  957.000     0032       100     CALL SUB11S
  958.000     0033       101     IF(SF.LT.0.99.OR.SF.GT.1.01)GO TO 10
  959.000     0034               IF(NUG.EQ.0)RETURN
  960.000     0035               IF(IFLOG.EQ.1)WRITE(IOUT,600)HW,B
  961.000     0036               IF(IFLOG.EQ.2)WRITE(IOUT,601)HW,H2
  962.000     0037               IF(IFLOG.EQ.3)WRITE(IOUT,602)HW,H2
  963.000     0038       10      RETURN
  964.000              C         *********************************************************
  965.000              C         Format Statements
  966.000                C     ***********************************************************
  967.000                C
  968.000     0039       600   FORMAT(' ',12X,'Case B1(a) - HW > B ie.',F7.2,' > ',F7.2)
  969.000     0040       601   FORMAT(' ',12X,'Case B1(b) - HW > H2 ie.',F7.2,' > ',F7.2)
  970.000     0041       602   FORMAT(' ',12X,'Case B1(c) - HW < H2 ie.',F7.2,' < ',F7.2)
  971.000     0042             END
```

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 *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

 *OPTIONS IN EFFECT*  NAME = SUB5    , LINECNT =       57

 *STATISTICS*    SOURCE STATEMENTS =       42,PROGRAM SIZE =     1976

 *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
  972.000     0001                SUBROUTINE SUB6
  973.000     0002                IMPLICIT REAL*8(A-H,K,O-Z)
  974.000              C          * * * * * * * * * * *
  975.000              C          *    Case B2          *
  976.000              C          * * * * * * * * * * *
  977.000              C
  978.000              C          ***************************************************
  979.000              C          Dimensions
  980.000              C          ***************************************************
  981.000              C
  982.000     0003                COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
  983.000                        *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
  984.000                        *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
  985.000                        *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
  986.000              C
  987.000              C
  988.000     0004                SAVEHW=HW
  989.000     0005                SS=H2*(1.-DCOTAN(AI2)*DTAN(AI1))+B*DCOTAN(BETA)*DTAN(AI1)
  990.000                        &    -XB*DTAN(AI1)
  991.000     0006                IF(HW.GT.SS)HW=SS
  992.000     0007                W=GAMMA/2.*(DCOTAN(BETA)*(Z(N)**2-Z(N+1)**2)+H1*(2.*A
  993.000                        &  *DCOTAN(BETA)-2.*H2*DCOTAN(AI2)-H1*DCOTAN(AI1)-2.*XB)
  994.000                        &  +(H2*DCOTAN(AI2)+XB+H1*DCOTAN(AI1)-B*DCOTAN(BETA))**2
  995.000                        &  *DTAN(BETA))
  996.000     0008                P0=0.0
  997.000     0009                P2=GAMMAW*(H2*(1.-DCOTAN(AI2)*DTAN(BETA))-XB*DTAN(BETA))
  998.000     0010                P3=GAMMAW*(HW*(1.-DCOTAN(AI1)*DTAN(BETA))+DTAN(BETA)*(H2*X-XB))
  999.000     0011                P4=GAMMAW*ALPHA
 1000.000     0012                AT=1./DSIN(BETA)*(B-A)
 1001.000     0013                A12=1./DSIN(BETA)*(H2*DCOTAN(AI2)*DTAN(BETA)+XB*DTAN(BETA)-A)
 1002.000     0014                A3=1./DSIN(BETA)*(DCOTAN(AI1)*DTAN(BETA)*(HW-H2))
 1003.000     0015                A4=1./DSIN(BETA)*(B+DTAN(BETA)*(H2*X-HW*DCOTAN(AI1)-XB))
 1004.000     0016                IF(B-HW)1,2,2
 1005.000     0017         1      IFLOG=1
 1006.000     0018                GO TO 5
 1007.000     0019         2      IF(H2-HW)3,4,4
 1008.000     0020         3      IFLOG=2
 1009.000     0021                P4=0.0
 1010.000     0022                A4=1./DSIN(BETA)*(DTAN(BETA)*(H2*(DCOTAN(AI1)-DCOTAN(AI2))
 1011.000                        &    -HW*DCOTAN(AI1)-XB)+HW)
 1012.000     0023                V=0.0
 1013.000     0024                GO TO 6
 1014.000     0025         4      IFLOG=3
 1015.000     0026                V=0.0
 1016.000     0027                U=0.0
 1017.000     0028                GO TO 7
 1018.000     0029         5      V=GAMMAW*ALPHA**2/2.
 1019.000     0030         6      U=0.5*((A12)*(P0+P2)+A3*(P2+P3)+A4*(P3+P4))
 1020.000     0031         7      Y=T*(Z(N+1)*(1.+DCOTAN(BETA)*DTAN(AI1))-H1*(1.+DCOTAN(BETA)
 1021.000                        &  *DTAN(AI1))+H2*DTAN(AI1)*(DCOTAN(BETA)+DCOTAN(AI2))
 1022.000                        &  -XB*DTAN(AI1))
 1023.000     0032                IF(NUNIT)99,99,100
 1024.000     0033        99      CALL SUB11I
 1025.000     0034                GO TO 101
 1026.000     0035       100      CALL SUB11S
 1027.000     0036         101   IF(SF.LT.0.99.OR.SF.GT.1.01)GO TO 10
 1028.000     0037               IF(NUG.EQ.0)GO TO 10
 1029.000     0038               IF(IFLOG.EQ.1)WRITE(IOUT,600)HW,B
 1030.000     0039               IF(IFLOG.EQ.2)WRITE(IOUT,601)HW,H2
 1031.000     0040               IF(IFLOG.EQ.3)WRITE(IOUT,602)HW,H2
 1032.000     0041         10    HW=SAVEHW
 1033.000     0042               RETURN
 1034.000                  C     *********************************************************
 1035.000                  C     Format Statements
 1036.000                  C     *********************************************************
 1037.000                  C
 1038.000     0043         600   FORMAT(' ',12X,'Case B2(a) - HW > B ie.',F7.2,' > ',F7.2)
 1039.000     0044         601   FORMAT(' ',12X,'Case B2(b) - HW > H2 ie.',F7.2,' > ',F7.2)
 1040.000     0045         602   FORMAT(' ',12X,'Case B2(c) - HW < H2 ie.',F7.2,' < ',F7.2)
 1041.000     0046               END
```

```
  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = SUB6    , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       46,PROGRAM SIZE =     2500

  *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
1042.000   0001             SUBROUTINE SUB7
1043.000   0002             IMPLICIT REAL*8(A-H,K,O-Z)
1044.000            C       * * * * * * * * * * * *
1045.000            C       *    Case B3          *
1046.000            C       * * * * * * * * * * * *
1047.000            C
1048.000            C       ***********************************************************
1049.000            C       Dimensions
1050.000            C       ***********************************************************
1051.000            C
1052.000   0003             COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
1053.000                   *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
1054.000                   *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
1055.000                   *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
1056.000            C
1057.000            C
1058.000   0004             SAVEHW=HW
1059.000   0005             IF(HW.GT.H2)HW=H2
1060.000   0006             W=GAMMA/2.*K(N+1)*(2.*H2-(B+A))
1061.000   0007             P0=0.0
1062.000   0008             P2=GAMMAW*ALPHA
1063.000   0009             AT=1./DSIN(BETA)*(B-A)
1064.000   0010             A12=1./DSIN(BETA)*(B-A)
1065.000   0011             IF(B-HW)1,2,2
1066.000   0012     1       IFLOG=1
1067.000   0013             GO TO 3
1068.000   0014     2       IFLOG=2
1069.000   0015             V=0.0
1070.000   0016             U=0.0
1071.000   0017             GO TO 5
1072.000   0018     3       V=GAMMAW*ALPHA**2/2.
1073.000   0019     4       U=0.5*((A12)*(P0+P2))
1074.000   0020     5       Y=T*(Z(N+1)-H1)
1075.000   0021             IF(NUNIT)99,99,100
1076.000   0022     99      CALL SUB11I
1077.000   0023             GO TO 101
1078.000   0024     100     CALL SUB11S
1079.000   0025     101     IF(SF.LT.0.99.OR.SF.GT.1.01)GO TO 10
1080.000   0026             IF(NUG.EQ.0)GO TO 10
1081.000   0027             IF(IFLOG.EQ.1)WRITE(IOUT,600)HW,B
1082.000   0028             IF(IFLOG.EQ.2)WRITE(IOUT,601)HW,B
1083.000   0029     10      HW=SAVEHW
1084.000   0030             RETURN
1085.000            C       ************************************************************
1086.000            C       Format Statements
1087.000            C       ************************************************************
1088.000            C
1089.000   0031     600     FORMAT(' ',12X,'Case B3(a) - HW > B ie.',F7.2,' > ',F7.2)
1090.000   0032     601     FORMAT(' ',12X,'Case B3(b) - HW < B ie.',F7.2,' < ',F7.2)
1091.000   0033             END
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MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        SUB7        07-29-84    15:56:52        PAGE 0002

  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = SUB7    , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       33,PROGRAM SIZE =     1064

  *STATISTICS*  NO DIAGNOSTICS GENERATED
  1092.000     0001                SUBROUTINE SUB8
  1093.000     0002                IMPLICIT REAL*8(A-H,K,O-Z)
  1094.000               C         * * * * * * * * * * * *
  1095.000               C         *    Case C1          *
  1096.000               C         * * * * * * * * * * * *
  1097.000               C
  1098.000               C         ***********************************************************
  1099.000               C         Dimensions
  1100.000               C         ***********************************************************
  1101.000               C
  1102.000     0003                COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
  1103.000                        *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
  1104.000                        *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
  1105.000                        *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
  1106.000               C
  1107.000               C
  1108.000     0004                W=GAMMA/2.*(H1**2*DCOTAN(AI1)+2*H1*(B*DCOTAN(BETA)
  1109.000                        &  -H1*DCOTAN(AI1)-XB-H2*DCOTAN(AI2))-(A*DCOTAN(BETA)
  1110.000                        &  -XB-H2*DCOTAN(AI2))**2*DTAN(AI1)-(B-H2)**2*DCOTAN(BETA)
  1111.000                        &  +(A-H2)**2*DCOTAN(BETA))
  1112.000     0005                P2=0.0
  1113.000     0006                P3=GAMMAW*(H2*DTAN(BETA)*X-XB*DTAN(BETA)+HW*(1.-DCOTAN(AI1)
  1114.000                        &*DTAN(BETA)))
  1115.000     0007                P4=GAMMAW*ALPHA
  1116.000     0008                AT=1./DSIN(BETA)*(B-A)
  1117.000     0009                A3=1./DSIN(BETA)*(HW*DCOTAN(AI1)*DTAN(BETA)+XB*DTAN(BETA)
  1118.000                        &    -A-H2*DTAN(BETA)*X)
  1119.000     0010                A4=1./DSIN(BETA)*(B-H2*X*DTAN(BETA)-XB*DTAN(BETA)
  1120.000                        &    -HW*DCOTAN(AI1)*DTAN(BETA))
  1121.000     0011                IF(B-HW)1,2,2
  1122.000     0012      1         IFLOG=1
  1123.000     0013                GO TO 5
  1124.000     0014      2         IF(R-HW)3,4,4
  1125.000     0015      3         IFLOG=2
  1126.000     0016                P4=0.0
  1127.000     0017                A4=1./DSIN(BETA)*(DTAN(BETA)*(H2*X-HW*DCOTAN(AI1)-XB)+HW)
  1128.000     0018                V=0.0
  1129.000     0019                GO TO 6
  1130.000     0020      4         IFLOG=3
  1131.000     0021                V=0.0
  1132.000     0022                U=0.0
  1133.000     0023                GO TO 7
  1134.000     0024      5         V=GAMMAW*ALPHA**2/2.
  1135.000     0025      6         U=0.5*((P2+P3)*A3+(P3+P4)*A4)
  1136.000     0026      7         Y=T*Z(N+1)
  1137.000     0027                IF(NUNIT)99,99,100
  1138.000     0028      99        CALL SUB11I
  1139.000     0029                GO TO 101
  1140.000     0030      100       CALL SUB11S
  1141.000     0031      101       IF(SF.LT.0.99.OR.SF.GT.1.01)GO TO 10
  1142.000     0032                IF(NUG.EQ.0)RETURN
  1143.000     0033                IF(IFLOG.EQ.1)WRITE(IOUT,600)HW,B
  1144.000     0034                IF(IFLOG.EQ.2)WRITE(IOUT,601)HW,R
  1145.000     0035                IF(IFLOG.EQ.3)WRITE(IOUT,602)HW,R
  1146.000     0036      10        RETURN
```

```
 1147.000                C     ************************************************************
 1148.000                C     Format Statements
 1149.000                C     ************************************************************
 1150.000                C
 1151.000     0037       600   FORMAT(' ',12X,'Case C1(a) - HW > B ie.',F7.2,' > ',F7.2)
 1152.000     0038       601   FORMAT(' ',12X,'Case C1(b) - HW > R ie.',F7.2,' > ',F7.2)
 1153.000     0039       602   FORMAT(' ',12X,'Case C1(c) - HW < R ie.',F7.2,' < ',F7.2)
 1154.000     0040             END
```

```
  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = SUB8    , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       40,PROGRAM SIZE =     2064

  *STATISTICS*  NO DIAGNOSTICS GENERATED
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```
 1155.000     0001              SUBROUTINE SUB9
 1156.000     0002              IMPLICIT REAL*8(A-H,K,O-Z)
 1157.000                  C    * * * * * * * * * * *
 1158.000                  C    *    Case C2         *
 1159.000                  C    * * * * * * * * * * *
 1160.000                  C
 1161.000                  C    ******************************************************
 1162.000                  C    Dimensions
 1163.000                  C    ******************************************************
 1164.000                  C
 1165.000     0003              COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
 1166.000                      *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
 1167.000                      *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
 1168.000                      *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
 1169.000                  C
 1170.000                  C
 1171.000     0004              SAVEHW=HW
 1172.000     0005              SS=H2*(1.-DCOTAN(AI2)*DTAN(AI1))+B*DCOTAN(BETA)*DTAN(AI1)
 1173.000                      &    -XB*DTAN(AI1)
 1174.000     0006              IF(HW.GT.SS)HW=SS
 1175.000     0007              W=GAMMA/2.*(DTAN(AI1)*((B*DCOTAN(BETA)-H2*DCOTAN(AI2)-XB)**2
 1176.000                      &  -(A*DCOTAN(BETA)-H2*DCOTAN(AI2)-XB)**2)
 1177.000                      &  -DCOTAN(BETA)*((B-H2)**2-(A-H2)**2))
 1178.000     0008              P2=0.0
 1179.000     0009              P3=GAMMAW*(H2*DTAN(BETA)*X-XB*DTAN(BETA)+HW*(1.-DCOTAN(AI1)
 1180.000                      &    *DTAN(BETA)))
 1181.000     0010              P4=GAMMAW*ALPHA
 1182.000     0011              AT=1./DSIN(BETA)*(B-A)
 1183.000     0012              A3=1./DSIN(BETA)*(HW*DCOTAN(AI1)*DTAN(BETA)+XB*DTAN(BETA)
 1184.000                      &    -A-H2*DTAN(BETA)*X)
 1185.000     0013              A4=1./DSIN(BETA)*(B-H2*X*DTAN(BETA)-XB*DTAN(BETA)
 1186.000                      &    -HW*DCOTAN(AI1)*DTAN(BETA))
 1187.000     0014              IF(B-HW)1,2,2
 1188.000     0015         1    IFLOG=1
 1189.000     0016              GO TO 5
 1190.000     0017         2    IF(R-HW)3,4,4
 1191.000     0018         3    IFLOG=2
 1192.000     0019              P4=0.0
 1193.000     0020              A4=1./DSIN(BETA)*(DTAN(BETA)*(H2*X-HW*DCOTAN(AI1)-XB)+HW)
 1194.000     0021              V=0.0
 1195.000     0022              GO TO 6
 1196.000     0023         4    IFLOG=3
 1197.000     0024              V=0.0
 1198.000     0025              U=0.0
 1199.000     0026              GO TO 7
 1200.000     0027         5    V=GAMMAW*ALPHA**2/2.
 1201.000     0028         6    U=0.5*((P2+P3)*A3+(P3+P4)*A4)
 1202.000     0029         7    Y=T*(Z(N+1)*(1.-DTAN(AI1)*DCOTAN(BETA))+DTAN(AI1)*((H1+H2)
 1203.000                      &*DCOTAN(BETA)-H1*DCOTAN(AI1)-XB-H2*DCOTAN(AI2)))
 1204.000     0030              IF(NUNIT)99,99,100
 1205.000     0031        99    CALL SUB11I
 1206.000     0032              GO TO 101
 1207.000     0033       100    CALL SUB11S
 1208.000     0034       101    IF(SF.LT 0.99.OR.SF.GT.1.01)GO TO 10
 1209.000     0035              IF(NUG.EQ.0)GO TO 10
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```
  1210.000     0036                IF(IFLOG.EQ.1)WRITE(IOUT,600)HW,B
  1211.000     0037                IF(IFLOG.EQ.2)WRITE(IOUT,601)HW,R
  1212.000     0038                IF(IFLOG.EQ.3)WRITE(IOUT,602)HW,R
  1213.000     0039         10     HW=SAVEHW
  1214.000     0040                RETURN
  1215.000                  C      ***********************************************************
  1216.000                  C      Format Statements
  1217.000                  C      ***********************************************************
  1218.000                  C
  1219.000     0041         600    FORMAT(' ',12X,'Case C2(a) - HW > B ie.',F7.2,' > ',F7.2)
  1220.000     0042         601    FORMAT(' ',12X,'Case C2(b) - HW > R ie.',F7.2,' > ',F7.2)
  1221.000     0043         602    FORMAT(' ',12X,'Case C2(c) - HW < R ie.',F7.2,' < ',F7.2)
  1222.000     0044                END
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MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        SUB9        07-29-84     15:56:53        PAGE 0003


  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = SUB9    , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       44,PROGRAM SIZE =     2232

  *STATISTICS*  NO DIAGNOSTICS GENERATED
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MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        SUB10       07-29-84     15:56:54         PAGE 0001

1223.000     0001                  SUBROUTINE SUB10
1224.000     0002                  IMPLICIT REAL*8(A-H,K,O-Z)
1225.000                   C       * * * * * * * * * * * *
1226.000                   C       *    Case D1          *
1227.000                   C       * * * * * * * * * * * *
1228.000                   C
1229.000                   C       *********************************************************
1230.000                   C       Dimensions
1231.000                   C       *********************************************************
1232.000                   C
1233.000     0003                  COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
1234.000                          *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
1235.000                          *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
1236.000                          *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
1237.000                   C
1238.000                   C
1239.000     0004                  W=GAMMA/2.*(DCOTAN(BETA)*(Z(N)**2-Z(N+1)**2))
1240.000     0005                  P2=0.0
1241.000     0006                  P4=GAMMAW*ALPHA
1242.000     0007                  AT=1./DSIN(BETA)*(B-A)
1243.000     0008                  A34=1./DSIN(BETA)*(K(N+1)*DTAN(BETA))
1244.000     0009                  IF(B-HW)1,2,2
1245.000     0010          1       IFLOG=1
1246.000     0011                  GO TO 3
1247.000     0012          2       IFLOG=2
1248.000     0013                  V=0.0
1249.000     0014                  U=0.0
1250.000     0015                  GO TO 5
1251.000     0016          3       V=GAMMAW*ALPHA**2/2.
1252.000     0017          4       U=0.5*A34*(P2+P4)
1253.000     0018          5       Y=T*Z(N+1)
1254.000     0019                  IF(NUNIT)99,99,100
1255.000     0020          99      CALL SUB11I
1256.000     0021                  GO TO 101
1257.000     0022          100     CALL SUB11S
1258.000     0023          101     IF(SF.LT.0.99.OR.SF.GT.1.01)GO TO 10
1259.000     0024                  IF(NUG.EQ.0)RETURN
1260.000     0025                  IF(IFLOG.EQ.1)WRITE(IOUT,600)HW,B
1261.000     0026                  IF(IFLOG.EQ.2)WRITE(IOUT,601)HW,B
1262.000     0027          10      RETURN
1263.000                   C       *********************************************************
1264.000                   C       Format Statements
1265.000                   C       *********************************************************
1266.000                   C
1267.000     0028          600     FORMAT(' ',12X,'Case D1(a) - HW > B ie.',F7.2,' > ',F7.2)
1268.000     0029          601     FORMAT(' ',12X,'Case D1(b) - HW < B ie.',F7.2,' < ',F7.2)
1269.000     0030                  END
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  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = SUB10    , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =        30,PROGRAM SIZE =      1076

  *STATISTICS*  NO DIAGNOSTICS GENERATED
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```
 1270.000     0001                SUBROUTINE SUB11S
 1271.000     0002                IMPLICIT REAL*8(A-H,K,O-Z)
 1272.000               C         * * * * * * * * * * * * * * * * * * * * * *
 1273.000               C         *  Calculate Factor of Safety (S.I. Units)  *
 1274.000               C         * * * * * * * * * * * * * * * * * * * * * *
 1275.000               C
 1276.000               C         *************************************************************
 1277.000               C         Dimensions
 1278.000               C         *************************************************************
 1279.000               C
 1280.000     0003                COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
 1281.000                        *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
 1282.000                        *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
 1283.000                        *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
 1284.000               C
 1285.000               C
 1286.000     0004                TOP=C*AT+DTAN(PHI)*(W*DCOS(BETA)-U-(V-Y)*DSIN(BETA))
 1287.000     0005                BOT=W*DSIN(BETA)+(V-Y)*DCOS(BETA)
 1288.000     0006                SF=TOP/BOT
 1289.000     0007                IF(SF-0.99)1,2,2
 1290.000     0008      1         IA=IA+1
 1291.000     0009                IC=0
 1292.000     0010                RETURN
 1293.000     0011      2         IF(1.01-SF)7,7,4
 1294.000     0012      3         IA=IA+1
 1295.000     0013                IC=0
 1296.000     0014                RETURN
 1297.000     0015      4         MAG=1
 1298.000     0016                IF(IWRITE)5,6,5
 1299.000     0017      5         NUG=0
 1300.000     0018      15        IA=IA+1
 1301.000     0019                IC=0
 1302.000     0020                IS1=IS
 1303.000     0021                N1=N
 1304.000     0022                SF1=SF
 1305.000     0023                NMIN11=NMIN1
 1306.000     0024                W1=W
 1307.000     0025                AT1=AT
 1308.000     0026                U1=U
 1309.000     0027                V1=V
 1310.000     0028                Y1=Y
 1311.000     0029                K1=K(N+1)
 1312.000     0030                Z1=Z(N+1)
 1313.000     0031                RETURN
 1314.000     0032      6         NMIN1=N-1
 1315.000     0033                WRITE(IOUT,600)IS,N,SF,NMIN1,N,W,NMIN1,N,AT,NMIN1,
 1316.000                        1N,U,N,V,N,Y,NMIN1,N,K(N+1),N,Z(N+1)
 1317.000     0034                DFT=SUMKN+K(N+1)
 1318.000     0035                DL(N)=DFT
 1319.000     0036                WRITE(IOUT,602)DFT
 1320.000     0037                IWRITE=1
 1321.000     0038                NUG=1
 1322.000     0039                GO TO 15
 1323.000     0040      7         IF(IWRITE)8,9,8
 1324.000     0041      8         NMIN=N-1
 1325.000      0042              WRITE(IOUT,601)IS1,N1,SF1,NMIN11,N1,W1,NMIN11,N1,AT1,NMIN11,
 1326.000                       1N1,U1,N1,V1,N1,Y1,NMIN11,N1,K1,N1,Z1
 1327.000      0043              DFT1=SUMKN+K1
 1328.000      0044              DU(N)=DFT1
 1329.000      0045              WRITE(IOUT,602)DFT1
 1330.000      0046        9     IF(IS-1)10,11,10
 1331.000      0047       10     IA=IA+1
 1332.000      0048              IC=0
 1333.000      0049              IWRITE=0
 1334.000      0050              RETURN
 1335.000      0051       11     IF(MAG)12,12,13
 1336.000      0052       12     IA=IA+1
 1337.000      0053              IC=0
 1338.000      0054              RETURN
 1339.000      0055       13     WRITE(ITERMO,400)
 1340.000      0056              READ(ITERMI,300)IS
 1341.000      0057              IF(IS.EQ.2)GO TO 14
 1342.000      0058              Z(N+1)=Z1
 1343.000      0059              K(N+1)=K1
 1344.000      0060              N=N+1
 1345.000      0061              IC=1
 1346.000      0062              RETURN
 1347.000      0063       14     IA=IA+1
 1348.000      0064              IC=0
 1349.000      0065              IWRITE=0
 1350.000      0066              RETURN
 1351.000                 C      ************************************************************
 1352.000                 C      Format Statements
 1353.000                 C      ************************************************************
 1354.000                 C
 1355.000      0067      300     FORMAT(I1)
 1356.000      0068      400     FORMAT(//'Do you wish to continue with solution 1 or'/
 1357.000                       1       'search for solution 2?'/'Enter 1 or 2')
 1358.000      0069      600     FORMAT('-',10X,'Solution number',I3,'    Crack number',I3,
 1359.000                       1       '        (Lower limit) '/
 1360.000                       1       ' ',12X,'Factor of Safety',81('.'),'(SF)',2X,'=',F10.4/
 1361.000                       1       ' ',12X,'Weight of failed wedge between cracks',I3,
 1362.000                       1       ' and',I3,51('.'),'(W)',2X,'=',F10.2,' kN'/
 1363.000                       1       ' ',12X,'Total area of the failure plane, of unit',
 1364.000                       1       ' depth, between cracks',I3,' and',I3,25('.'),
 1365.000                       1       '(At)',2X,'=',F10.2,' sq m'/
 1366.000                       1       ' ',12X,'Total uplift force due to water pressure',
 1367.000                       1       ' acting on the failure plane between cracks',I3,
 1368.000                       1       ' and',I3,5('.'),'(U)',2X,'=',F10.2,' kN'/
 1369.000                       1       ' ',12X,'Force applied to the failed wedge by the ',
 1370.000                       1       'water in crack',I3,40('.'),'(V)',2X,'=',F10.2,' kN'/
 1371.000                       1       ' ',12X,'Resisting force due to tensile strength ',
 1372.000                       1       'across the potential crack',I3,29('.'),'(Y)',
 1373.000                       1       2X,'=',F10.2,' kN'/
 1374.000                       1       ' ',12X,'Horizontal distance between cracks',I3,
 1375.000                       1       ' and',I3,51('.'),'(Kn+1)',2X,'=',F10.2,' m'/
 1376.000                       1       ' ',12X,'Depth of crack',I3,' below surface',64('.'),
 1377.000                       1       '(Zn+1)',2X,'=',F10.2,' m')
 1378.000      0070      602     FORMAT(13X,'Distance to crack from toe of slope',52('.'),
 1379.000                       1       '(SUMKN + Kn+1)',2X,'=',F10.2,' m'/)
 1380.000     0071         601   FORMAT('-',10X,'Solution number',I3,'    Crack number',I3,
 1381.000                        1         '        (Upper limit) '/
 1382.000                        1         ' ',12X,'Factor of Safety',81('.'),'(SF)',2X,'=',F10.4/
 1383.000                        1         ' ',12X,'Weight of failed wedge between cracks',I3,
 1384.000                        1         ' and',I3,51('.'),'(W)',2X,'=',F10.2,' kN'/
 1385.000                        1         ' ',12X,'Total area of the failure plane, of unit',
 1386.000                        1         ' depth, between cracks',I3,' and',I3,25('.'),
 1387.000                        1         '(At)',2X,'=',F10.2,' sq m'/
 1388.000                        1         ' ',12X,'Total uplift force due to water pressure',
 1389.000                        1         ' acting on the failure plane between cracks',I3,
 1390.000                        1         ' and',I3,5('.'),'(U)',2X,'=',F10.2,' kN'/
 1391.000                        1         ' ',12X,'Force applied to the failed wedge by the ',
 1392.000                        1         'water in crack',I3,40('.'),'(V)',2X,'=',F10.2,' kN'/
 1393.000                        1         ' ',12X,'Resisting force due to tensile strength ',
 1394.000                        1         'across the potential crack',I3,29('.'),'(Y)',
 1395.000                        1         2X,'=',F10.2,' kN'/
 1396.000                        1         ' ',12X,'Horizontal distance between cracks',I3,
 1397.000                        1         ' and',I3,51('.'),'(Kn+1)',2X,'=',F10.2,' m'/
 1398.000                        1         ' ',12X,'Depth of crack',I3,' below surface',64('.'),
 1399.000                        1         '(Zn+1)',3X,'=',F10.2,' m')
 1400.000     0072                 END
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MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        SUB11S      07-29-84     15:56:55        PAGE 0004

  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = SUB11S  , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       72,PROGRAM SIZE =     3554

  *STATISTICS*  NO DIAGNOSTICS GENERATED
  1401.000     0001                 SUBROUTINE SUB11I
  1402.000     0002                 IMPLICIT REAL*8(A-H,K,O-Z)
  1403.000               C          * * * * * * * * * * * * * * * * * * * * * * * * * *
  1404.000               C          *  Calculate Factor of Safety (Imperial Units)  *
  1405.000               C          * * * * * * * * * * * * * * * * * * * * * * * * * *
  1406.000               C
  1407.000               C          ***********************************************************
  1408.000               C          Dimensions
  1409.000               C          ***********************************************************
  1410.000               C
  1411.000     0003                 COMMON IIN,IOUT,H1,H2,HW,AI1,AI2,XB,BETA,Z(100),K(100),A,B,
  1412.000                         *ALPHA,W,GAMMA,GAMMAW,AT,IA,IS,SF,ITERMI,ITERMO,SUMKN,
  1413.000                         *U,V,Y,T,RT,C,PHI,X,S,R,DELTA,N,IC,NUNIT,IWRITE,MAG,NUG,
  1414.000                         *BETAM,PHIM,CM,TM,DU(100),DL(100),IOUT2,IOUT3,JQR
  1415.000               C
  1416.000               C
  1417.000     0004                 TOP=C*AT+DTAN(PHI)*(W*DCOS(BETA)-U-(V-Y)*DSIN(BETA))
  1418.000     0005                 BOT=W*DSIN(BETA)+(V-Y)*DCOS(BETA)
  1419.000     0006                 SF=TOP/BOT
  1420.000     0007                 IF(SF-0.99)1,2,2
  1421.000     0008      1          IA=IA+1
  1422.000     0009                 IC=0
  1423.000     0010                 RETURN
  1424.000     0011      2          IF(1.01-SF)7,7,4
  1425.000     0012      3          IA=IA+1
  1426.000     0013                 IC=0
  1427.000     0014                 RETURN
  1428.000     0015      4          MAG=1
  1429.000     0016                 IF(IWRITE)5,6,5
  1430.000     0017      5          NUG=0
  1431.000     0018      15         IA=IA+1
  1432.000     0019                 IC=0
  1433.000     0020                 IS1=IS
  1434.000     0021                 N1=N
  1435.000     0022                 SF1=SF
  1436.000     0023                 NMIN11=NMIN1
  1437.000     0024                 W1=W
  1438.000     0025                 AT1=AT
  1439.000     0026                 U1=U
  1440.000     0027                 V1=V
  1441.000     0028                 Y1=Y
  1442.000     0029                 K1=K(N+1)
  1443.000     0030                 Z1=Z(N+1)
  1444.000     0031                 RETURN
  1445.000     0032      6          NMIN1=N-1
  1446.000     0033                 WRITE(IOUT,600)IS,N,SF,NMIN1,N,W,NMIN1,N,AT,NMIN1,
  1447.000                         1N,U,N,V,N,Y,NMIN1,N,K(N+1),N,Z(N+1)
  1448.000     0034                 DFT=SUMKN+K(N+1)
  1449.000     0035                 DL(N)=DFT
  1450.000     0036                 WRITE(IOUT,602)DFT
  1451.000     0037                 IWRITE=1
  1452.000     0038                 NUG=1
  1453.000     0039                 GO TO 15
  1454.000     0040      7          IF(IWRITE)8,9,8
  1455.000     0041      8          NMIN=N-1
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```
              WRITE(IOUT,601)IS1,N1,SF1,NMIN11,N1,W1,NMIN11,N1,AT1,NMIN11,
             1N1,U1,N1,V1,N1,Y1,NMIN11,N1,K1,N1,Z1
              DFT1=SUMKN+K1
              DU(N)=DFT1
              WRITE(IOUT,602)DFT1
      9       IF(IS-1)10,11,10
      10      IA=IA+1
              IC=O
              IWRITE=O
              RETURN
      11      IF(MAG)12,12,13
      12      IA=IA+1
              IC=O
              RETURN
      13      WRITE(ITERMO,400)
              READ(ITERMI,300)IS
              IF(IS.EQ.2)GO TO 14
              Z(N+1)=Z1
              K(N+1)=K1
              N=N+1
              IC=1
              RETURN
      14      IA=IA+1
              IC=O
              IWRITE=O
              RETURN
      C       ***********************************************************
      C       Format Statements
      C       ***********************************************************
      C
      300     FORMAT(I1)
      400     FORMAT(//'Do you wish to continue with solution 1 or'/
             1        'search for solution 2?'/'Enter 1 or 2')
      600     FORMAT('-',10X,'Solution number',I3,'    Crack number',I3,
             1        '         (Lower limit) '/
             1        ' ',12X,'Factor of Safety',81('.'),'(SF)',2X,'=',F10.4/
             1        ' ',12X,'Weight of failed wedge between cracks',I3,
             1        ' and',I3,51('.'),'(W)',2X,'=',F10.2,' lbs'/
             1        ' ',12X,'Total area of the failure plane, of unit',
             1        ' depth, between cracks',I3,' and',I3,25('.'),
             1        '(At)',2X,'=',F10.2,' sq ft'/
             1        ' ',12X,'Total uplift force due to water pressure',
             1        ' acting on the failure plane between cracks',I3,
             1        ' and',I3,5('.'),'(U)',2X,'=',F10.2,' lbs'/
             1        ' ',12X,'Force applied to the failed wedge by the ',
             1        'water in crack',I3,40('.'),'(V)',2X,'=',F10.2,' lbs'/
             1        ' ',12X,'Resisting force due to tensile strength ',
             1        'across the potential crack',I3,29('.'),'(Y)',
             1        2X,'=',F10.2,' lbs'/
             1        ' ',12X,'Horizontal distance between cracks',I3,
             1        ' and',I3,51('.'),'(Kn+1)',2X,'=',F10.2,' ft'/
             1        ' ',12X,'Depth of crack',I3,' below surface',64('.'),
             1        '(Zn+1)',2X,'=',F10.2,' ft')
      602     FORMAT(13X,'Distance to crack from toe of slope',52('.'),
             1        '(SUMKN + Kn+1)',2X,'=',F10.2,' ft'/)
```

```
 1511.000     0071          601   FORMAT('-',10X,'Solution number',I3,'    Crack number',I3,
 1512.000                        1         '        (Upper limit) '/
 1513.000                        1         ' ',12X,'Factor of Safety',81('.'),'(SF)',2X,'=',F10.4/
 1514.000                        1         ' ',12X,'Weight of failed wedge between cracks',I3,
 1515.000                        1         ' and',I3,51('.'),'(W)',2X,'=',F10.2,' lbs'/
 1516.000                        1         ' ',12X,'Total area of the failure plane, of unit',
 1517.000                        1         ' depth, between cracks',I3,' and',I3,25('.'),
 1518.000                        1         '(At)',2X,'=',F10.2,' sq ft'/
 1519.000                        1         ' ',12X,'Total uplift force due to water pressure',
 1520.000                        1         ' acting on the failure plane between cracks',I3,
 1521.000                        1         ' and',I3,5('.'),'(U)',2X,'=',F10.2,' lbs'/
 1522.000                        1         ' ',12X,'Force applied to the failed wedge by the ',
 1523.000                        1         'water in crack',I3,40('.'),'(V)',2X,'=',F10.2,' lbs'/
 1524.000                        1         ' ',12X,'Resisting force due to tensile strength ',
 1525.000                        1         'across the potential crack',I3,29('.'),'(Y)',
 1526.000                        1         2X,'=',F10.2,' lbs'/
 1527.000                        1         ' ',12X,'Horizontal distance between cracks',I3,
 1528.000                        1         ' and',I3,51('.'),'(Kn+1)',2X,'=',F10.2,' ft'/
 1529.000                        1         ' ',12X,'Depth of crack',I3,' below surface',64('.'),
 1530.000                        1         '(Zn+1)',2X,'=',F10.2,' ft')
 1531.000     0072                END
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        SUB11I      07-29-84    15:56:55        PAGE 0004

   *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

   *OPTIONS IN EFFECT*  NAME = SUB11I   , LINECNT =       57

   *STATISTICS*    SOURCE STATEMENTS =       72,PROGRAM SIZE =     3570

   *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        RAND        07-29-84     15:56:56          PAGE 0001

  1532.000              C
  1533.000     0001           FUNCTION RAND(IX)
  1534.000              C
  1535.000              C     Portable random number generator
  1536.000              C     using the recursion
  1537.000              C     IX =IX*A mod P
  1538.000              C
  1539.000              C     reference: Schrage, L. "A More Portable Fortran Random Number
  1540.000              C                  Generator". ACM Transactions on Mathematical
  1541.000              C                  Software, Vol. 5, No. 2, June 1979, pp 132-138.
  1542.000              C
  1543.000              C
  1544.000     0002           INTEGER A,P,IX,B15,B16,XHI,XALO,LEFTLO,FHI,K
  1545.000     0003           DATA A/16807/,B15/32768/,B16/65536/,P/2147483647/
  1546.000              C
  1547.000     0004           XHI=IX/B16
  1548.000     0005           XALO=(IX-XHI*B16)*A
  1549.000     0006           LEFTLO=XALO/B16
  1550.000     0007           FHI=XHI*A+LEFTLO
  1551.000     0008           K=FHI/B15
  1552.000     0009           IX=(((XALO-LEFTLO*B16)-P)+(FHI-K*B15)*B16)+K
  1553.000     0010           IF(IX.LT.O) IX=IX+P
  1554.000     0011           RAND=FLOAT(IX)*4.656612875E-10
  1555.000     0012           RETURN
  1556.000     0013           END
  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = RAND    , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       13,PROGRAM SIZE =      524

  *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        RNORMP       07-29-84     15:56:57         PAGE 0001

  1582.000     0001                  FUNCTION RNORMP(XMEAN,STD,IX)
  1583.000                   C
  1584.000                   C       Function used to obtain random samples from a normal
  1585.000                   C       distribution.
  1586.000                   C
  1587.000                   C       reference: Pritsker, A.A.B. & Pegden, C.D. "Introduction
  1588.000                   C                  to Simulation and Slam". John Wiley & Sons,
  1589.000                   C                  Inc., New York, 1979. p 566.
  1590.000                   C
  1591.000     0002                  INTEGER SWITCH
  1592.000     0003                  DATA SWITCH/0/
  1593.000     0004                  IF(SWITCH)1,1,2
  1594.000     0005          1       AQ=2.*RAND(IX)-1.
  1595.000     0006                  BQ=2.*RAND(IX)-1.
  1596.000     0007                  WQ=AQ*AQ+BQ*BQ
  1597.000     0008                  IF(WQ.GT.1.0)GO TO 1
  1598.000     0009                  RNORMP=(AQ*SQRT(-2.*ALOG(WQ)/WQ))*STD+XMEAN
  1599.000     0010                  SAVEP= (BQ*SQRT(-2.*ALOG(WQ)/WQ))*STD+XMEAN
  1600.000     0011                  SWITCH=1
  1601.000     0012                  GO TO 3
  1602.000     0013          2       RNORMP=SAVEP
  1603.000     0014                  SWITCH=0
  1604.000     0015          3       RETURN
  1605.000     0016                  END
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        RNORMB      07-29-84    15:56:57        PAGE 0002

  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = RNORMB   , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       16,PROGRAM SIZE =      654

  *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
 1557.000                 C
 1558.000     0001                 FUNCTION RNORMB(XMEAN,STD,IX)
 1559.000                 C
 1560.000                 C        Function used to obtain random samples from a normal
 1561.000                 C        distribution.
 1562.000                 C
 1563.000                 C        reference: Pritsker, A.A.B. & Pegden, C.D. "Introduction
 1564.000                 C                      to Simulation and Slam". John Wiley & Sons,
 1565.000                 C                      Inc., New York, 1979. p 566.
 1566.000                 C
 1567.000     0002                 INTEGER SWITCH
 1568.000     0003                 DATA SWITCH/O/
 1569.000     0004                 IF(SWITCH)1,1,2
 1570.000     0005        1        AQ=2.*RAND(IX)-1.
 1571.000     0006                 BQ=2.*RAND(IX)-1.
 1572.000     0007                 WQ=AQ*AQ+BQ*BQ
 1573.000     0008                 IF(WQ.GT.1.0)GO TO 1
 1574.000     0009                 RNORMB=(AQ*SQRT(-2.*ALOG(WQ)/WQ))*STD+XMEAN
 1575.000     0010                 SAVEB= (BQ*SQRT(-2.*ALOG(WQ)/WQ))*STD+XMEAN
 1576.000     0011                 SWITCH=1
 1577.000     0012                 GO TO 3
 1578.000     0013        2        RNORMB=SAVEB
 1579.000     0014                 SWITCH=O
 1580.000     0015        3        RETURN
 1581.000     0016                 END
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        RNORMP      07-29-84     15:56:57        PAGE 0002

  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = RNORMP  , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       16,PROGRAM SIZE =      654

  *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        RNORMC      07-29-84     15:56:58         PAGE 0001

  1606.000     0001                  FUNCTION RNORMC(XMEAN,STD,IX)
  1607.000                  C
  1608.000                  C        Function used to obtain random samples from a normal
  1609.000                  C        distribution.
  1610.000                  C
  1611.000                  C        reference: Pritsker, A.A.B. & Pegden, C.D. "Introduction
  1612.000                  C                    to Simulation and Slam". John Wiley & Sons,
  1613.000                  C                    Inc., New York, 1979. p 566.
  1614.000                  C
  1615.000     0002                  INTEGER SWITCH
  1616.000     0003                  DATA SWITCH/0/
  1617.000     0004                  IF(SWITCH)1,1,2
  1618.000     0005         1        AQ=2.*RAND(IX)-1.
  1619.000     0006                  BQ=2.*RAND(IX)-1.
  1620.000     0007                  WQ=AQ*AQ+BQ*BQ
  1621.000     0008                  IF(WQ.GT.1.0)GO TO 1
  1622.000     0009                  RNORMC=(AQ*SQRT(-2.*ALOG(WQ)/WQ))*STD+XMEAN
  1623.000     0010                  SAVEC= (BQ*SQRT(-2.*ALOG(WQ)/WQ))*STD+XMEAN
  1624.000     0011                  SWITCH=1
  1625.000     0012                  GO TO 3
  1626.000     0013         2        RNORMC=SAVEC
  1627.000     0014                  SWITCH=0
  1628.000     0015         3        RETURN
  1629.000     0016                  END
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        RNORMT      07-29-84     15:56:58        PAGE 0002

  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = RNORMT   , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       16,PROGRAM SIZE =      654

  *STATISTICS*  NO DIAGNOSTICS GENERATED
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```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        RNORMT      07-29-84     15:56:58         PAGE 0001

 1630.000     0001                FUNCTION RNORMT(XMEAN,STD,IX)
 1631.000                 C
 1632.000                 C       Function used to obtain random samples from a normal
 1633.000                 C       distribution.
 1634.000                 C
 1635.000                 C       reference: Pritsker, A.A.B. & Pegden, C.D. "Introduction
 1636.000                 C                   to Simulation and Slam". John Wiley & Sons,
 1637.000                 C                   Inc., New York, 1979. p 566.
 1638.000                 C
 1639.000     0002                INTEGER SWITCH
 1640.000     0003                DATA SWITCH/0/
 1641.000     0004                IF(SWITCH)1,1,2
 1642.000     0005        1       AQ=2.*RAND(IX)-1.
 1643.000     0006                BQ=2.*RAND(IX)-1.
 1644.000     0007                WQ=AQ*AQ+BQ*BQ
 1645.000     0008                IF(WQ.GT.1.0)GO TO 1
 1646.000     0009                RNORMT=(AQ*SQRT(-2.*ALOG(WQ)/WQ))*STD+XMEAN
 1647.000     0010                SAVET= (BQ*SQRT(-2.*ALOG(WQ)/WQ))*STD+XMEAN
 1648.000     0011                SWITCH=1
 1649.000     0012                GO TO 3
 1650.000     0013        2       RNORMT=SAVET
 1651.000     0014                SWITCH=0
 1652.000     0015        3       RETURN
 1653.000     0016                END
```

```
MTS  FORTRAN IV G COMPILER(21.8) WITH SDS SUPPORT        RNORMC      07-29-84     15:56:58        PAGE 0002

  *OPTIONS IN EFFECT*  NOID,EBCDIC,SOURCE,LIST,NODECK,LOAD,NOMAP

  *OPTIONS IN EFFECT*  NAME = RNORMC   , LINECNT =       57

  *STATISTICS*    SOURCE STATEMENTS =       16,PROGRAM SIZE =      654

  *STATISTICS*  NO DIAGNOSTICS GENERATED
```

APPENDIX B - Sample Problems

```
GS77_ .   1545_ _ _ _ _ _ _ _ _ 884545_ _ _ _ _ _ _ _ _ 884545_ _ _ .   . _ _ 884545_ _ _ _ _ _ _ _ _ 884545_ _ _ _ _ _ _ _ _ 8845/   . GS77

JOB NO. 884545       UNIVERSITY OF ALBERTA COMPUTING SERVICES  (SYSTEM AY284)                15:58:29    Sun Jul 29/84




                              User: GS77
                              Project no: CEA3

                              **** Obtained at      15:58:29    Sun Jul 29/84
                              **** Released at      15:58:31    Sun Jul 29/84
                              **** Lines printed     1902
                              **** Images printed      71
                              **** Pages printed       70
                                            '


 8888888888    8888888888         444     555555555555        444     555555555555
888888888888  888888888888       4444     555555555555       4444     555555555555
88        88  88        88      44 44     55                44 44     55
88        88  88        88     44  44     55               44  44     55
 88      88    88      88     44   44     55              44   44     55
  88888888      88888888     44444444444  555555555      44444444444  555555555
  88888888      88888888    444444444444  5555555555    444444444444  5555555555
 88      88    88      88         44            55          44            55
88        88  88        88         44             55         44             55
88        88  88        88         44             55         44             55
888888888888  888888888888         44     555555555555         44     555555555555
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               GGGGGGGGGG    SSSSSSSSSS   777777777777  777777777777
              GGGGGGGGGGGG  SSSSSSSSSSSS  77777777777   77777777777
              GG        GG  SS        SS  77      77    77      77
              GG            SS                   77           77
              GG            SSS                 77           77
              GG             SSSSSSSSS         77           77
              GG     GGGGG    SSSSSSSSS        77           77
              GG     GGGGG           SSS       77           77
              GG        GG            SS       77           77
              GG        GG  SS        SS       77           77
              GGGGGGGGGGGG  SSSSSSSSSSSS       77           77
               GGGGGGGGGG    SSSSSSSSSS        77           77

GS77 • *884545 • • • • • • • *884545 • • • • • • • *884545 • • • • • • • *884545 • • • • • • • *884545 • • • • • • • *884545 • *GS77
```

```
                    ***********************************************************
                    *                                                         *
                    *                          MBPSSF                         *
                    *       Multiple Block Plane Shear Slope Failure          *
                    *                                                         *
                    ***********************************************************


Testing the program *****  Base Case ********


Geometric Data
                Height of the upper slope..............................(H1)   =      6.00 m
                Height of the lower slope..............................(H2)   =     20.00 m
                Height of the water table..............................(Hw)   =     26.00 m
                Bench width............................................(Xb)   =     12.00 m
                Angle of the upper slope with the horizontal..........(Ai1)   =     60.00 deg
                Angle of the lower slope with the horizontal..........(Ai2)   =     70.00 deg
                Angle of the failure plane with the horizontal.......(Beta)   =      5.00 deg
                Incremental horizontal distance.....................(Delta)   =    0.1000 m


Material Properties
                Tensile strength of the rock............................(T)   =    70.000 kPa
                Effective cohesion on the failure surface...............(C)   =     7.000 kPa
                Density of rock in the failed wedge.................(Gamma)   =    21.600 kN/m3
                Density of water...................................(Gammaw)   =     9.810 kN/m3
                Effective angle of friction on the failure plane.....(Phi)   =     8.000 deg


*******************************************************************************
Run #  1     Type of Analysis: Deterministic (option 2)
*******************************************************************************


Solution number  1    Crack number  1        (Lower limit)
  Factor of Safety.............................................................................(SF)  =     0.9903
  Weight of failed wedge between cracks  0 and  1...............................................(W)  =   42079.51 kN
  Total area of the failure plane, of unit depth, between cracks  0 and  1.....................(At)  =      99.48 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  0 and  1.....(U)  =   19184.09 kN
  Force applied to the failed wedge by the water in crack  1....................................(V)  =    1473.37 kN
  Resisting force due to tensile strength across the potential crack  1.........................(Y)  =    1213.21 kN
  Horizontal distance between cracks  0 and  1...............................................(Kn+1)  =      99.10 m
  Depth of crack  1 below surface............................................................(Zn+1)  =      17.33 m
  Distance to crack from toe of slope.................................................(SUMKN + Kn+1)  =      99.10 m

  Case A1(a) - HW > B ie.  26.00 >     8.67

Solution number  1    Crack number  1        (Upper limit)
  Factor of Safety.............................................................................(SF)  =     1.0097
  Weight of failed wedge between cracks  0 and  1...............................................(W)  =   44581.48 kN
  Total area of the failure plane, of unit depth, between cracks  0 and  1.....................(At)  =     106.30 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  0 and  1.....(U)  =   20324.74 kN
  Force applied to the failed wedge by the water in crack  1....................................(V)  =    1373.98 kN
  Resisting force due to tensile strength across the potential crack  1.........................(Y)  =    1171.57 kN
  Horizontal distance between cracks  0 and  1...............................................(Kn+1)  =     105.90 m
  Depth of crack  1 below surface............................................................(Zn+1)  =      16.74 m
  Distance to crack from toe of slope...................................................(SUMKN + Kn+1)  =    105.90 m


Solution number  1    Crack number  2       (Lower limit)
  Factor of Safety..........................................................................(SF)  =    0.9930
  Weight of failed wedge between cracks  1 and  2............................................(W)  =   3142.64 kN
  Total area of the failure plane, of unit depth, between cracks  1 and  2..................(At)  =      8.93 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  1 and  2.....(U)  =    699.31 kN
  Force applied to the failed wedge by the water in crack  2.................................(V)  =   1249.13 kN
  Resisting force due to tensile strength across the potential crack  2......................(Y)  =   1117.07 kN
  Horizontal distance between cracks  1 and  2..........................................(Kn+1)  =      8.90 m
  Depth of crack  2 below surface.......................................................(Zn+1)  =     15.96 m
  Distance to crack from toe of slope..,................................................(SUMKN + Kn+1)  =    114.80 m

  Case D1(a) - HW > B ie.  26.00 >   10.04


Solution number  1    Crack number  2       (Upper limit)
  Factor of Safety..........................................................................(SF)  =    1.0094
  Weight of failed wedge between cracks  1 and  2............................................(W)  =   3245.96 kN
  Total area of the failure plane, of unit depth, between cracks  1 and  2..................(At)  =      9.24 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  1 and  2.....(U)  =    721.69 kN
  Force applied to the failed wedge by the water in crack  2.................................(V)  =   1245.02 kN
  Resisting force due to tensile strength across the potential crack  2......................(Y)  =   1115.24 kN
  Horizontal distance between cracks  1 and  2..........................................(Kn+1)  =      9.20 m
  Depth of crack  2 below surface.......................................................(Zn+1)  =     15.93 m
  Distance to crack from toe of slope...................................................(SUMKN + Kn+1)  =    115.10 m


Solution number  1    Crack number  3       (Lower limit)
  Factor of Safety..........................................................................(SF)  =    0.9959
  Weight of failed wedge between cracks  2 and  3............................................(W)  =   2030.77 kN
  Total area of the failure plane, of unit depth, between cracks  2 and  3..................(At)  =      6.02 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  2 and  3.....(U)  =    455.16 kN
  Force applied to the failed wedge by the water in crack  3.................................(V)  =   1164.35 kN
  Resisting force due to tensile strength across the potential crack  3......................(Y)  =   1078.50 kN
  Horizontal distance between cracks  2 and  3..........................................(Kn+1)  =      6.00 m
  Depth of crack  3 below surface.......................................................(Zn+1)  =     15.41 m
  Distance to crack from toe of slope...................................................(SUMKN + Kn+1)  =    121.10 m

  Case D1(a) - HW > B ie.  26.00 >   10.59


Solution number  1    Crack number  3       (Upper limit)
  Factor of Safety..........................................................................(SF)  =    1.0041
  Weight of failed wedge between cracks  2 and  3............................................(W)  =   2064.04 kN
  Total area of the failure plane, of unit depth, between cracks  2 and  3..................(At)  =      6.12 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  2 and  3.....(U)  =    462.49 kN
  Force applied to the failed wedge by the water in crack  3.................................(V)  =   1163.03 kN
  Resisting force due to tensile strength across the potential crack  3......................(Y)  =   1077.89 kN
  Horizontal distance between cracks  2 and  3..........................................(Kn+1)  =      6.10 m
  Depth of crack  3 below surface.......................................................(Zn+1)  =     15.40 m
  Distance to crack from toe of slope...................................................(SUMKN + Kn+1)  =    121.20 m


Solution number  1    Crack number  4       (Lower limit)
  Factor of Safety..........................................................................(SF)  =    1.0011
  Weight of failed wedge between cracks  3 and  4.....................................................(W)  =   1347.80 kN
  Total area of the failure plane, of unit depth, between cracks  3 and  4...........................(At)  =      4.12 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  3 and  4.....(U)  =    303.61 kN
  Force applied to the failed wedge by the water in crack  4..........................................(V)  =   1109.48 kN
  Resisting force due to tensile strength across the potential crack  4...............................(Y)  =   1052.78 kN
  Horizontal distance between cracks  3 and  4.....................................................(Kn+1)  =      4.10 m
  Depth of crack  4 below surface..................................................................(Zn+1)  =     15.04 m
  Distance to crack from toe of slope......................................................(SUMKN + Kn+1)  =    125.30 m

  Case D1(a) - HW > B ie.  26.00 >   10.96


Solution number  1    Crack number  4       (Upper limit)
  Factor of Safety...................................................................................(SF)  =    1.0011
  Weight of failed wedge between cracks  3 and  4.....................................................(W)  =   1347.80 kN
  Total area of the failure plane, of unit depth, between cracks  3 and  4...........................(At)  =      4.12 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  3 and  4.....(U)  =    303.61 kN
  Force applied to the failed wedge by the water in crack  4..........................................(V)  =   1109.48 kN
  Resisting force due to tensile strength across the potential crack  4...............................(Y)  =   1052.78 kN
  Horizontal distance between cracks  3 and  4.....................................................(Kn+1)  =      4.10 m
  Depth of crack  4 below surface..................................................................(Zn+1)  =     15.04 m
  Distance to crack from toe of slope......................................................(SUMKN + Kn+1)  =    125.30 m


Solution number  1    Crack number  5       (Lower limit)
  Factor of Safety...................................................................................(SF)  =    1.0031
  Weight of failed wedge between cracks  4 and  5.....................................................(W)  =    902.20 kN
  Total area of the failure plane, of unit depth, between cracks  4 and  5...........................(At)  =      2.81 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  4 and  5.....(U)  =    203.97 kN
  Force applied to the failed wedge by the water in crack  5..........................................(V)  =   1073.64 kN
  Resisting force due to tensile strength across the potential crack  5...............................(Y)  =   1035.64 kN
  Horizontal distance between cracks  4 and  5.....................................................(Kn+1)  =      2.80 m
  Depth of crack  5 below surface..................................................................(Zn+1)  =     14.79 m
  Distance to crack from toe of slope......................................................(SUMKN + Kn+1)  =    128.10 m

  Case D1(a) - HW > B ie.  26.00 >   11.21


Solution number  1    Crack number  5       (Upper limit)
  Factor of Safety...................................................................................(SF)  =    1.0031
  Weight of failed wedge between cracks  4 and  5.....................................................(W)  =    902.20 kN
  Total area of the failure plane, of unit depth, between cracks  4 and  5...........................(At)  =      2.81 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  4 and  5.....(U)  =    203.97 kN
  Force applied to the failed wedge by the water in crack  5..........................................(V)  =   1073.64 kN
  Resisting force due to tensile strength across the potential crack  5...............................(Y)  =   1035.64 kN
  Horizontal distance between cracks  4 and  5.....................................................(Kn+1)  =      2.80 m
  Depth of crack  5 below surface..................................................................(Zn+1)  =     14.79 m
  Distance to crack from toe of slope......................................................(SUMKN + Kn+1)  =    128.10 m


Solution number  1    Crack number  6       (Lower limit)
  Factor of Safety...................................................................................(SF)  =    1.0020
  Weight of failed wedge between cracks  5 and  6.....................................................(W)  =    603.77 kN
  Total area of the failure plane, of unit depth, between cracks  5 and  6...........................(At)  =      1.91 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  5 and  6.....(U)  =    136.85 kN
  Force applied to the failed wedge by the water in crack  6..........................................(V)  =   1049.65 kN
  Resisting force due to tensile strength across the potential crack  6...............................(Y)  =   1024.00 kN
  Horizontal distance between cracks  5 and  6.....................................................(Kn+1)  =      1.90 m
```

```
   Depth of crack  6 below surface.................................................................(Zn+1)  =    14.63 m
   Distance to crack from toe of slope.....................................................(SUMKN + Kn+1)  =   130.00 m

   Case D1(a) - HW > B ie.  26.00 >   11.37


Solution number  1    Crack number  6       (Upper limit)
   Factor of Safety.................................................................................(SF)  =   1.0020
   Weight of failed wedge between cracks  5 and  6...................................................(W)  =   603.77 kN
   Total area of the failure plane, of unit depth, between cracks  5 and  6.........................(At)  =     1.91 sq m
   Total uplift force due to water pressure acting on the failure plane between cracks  5 and  6.....(U)  =   136.85 kN
   Force applied to the failed wedge by the water in crack  6........................................(V)  =  1049.65 kN
   Resisting force due to tensile strength across the potential crack  6.............................(Y)  =  1024.00 kN
   Horizontal distance between cracks  5 and  6.................................................(Kn+1)  =     1.90 m
   Depth of crack  6 below surface..............................................................(Zn+1)  =    14.63 m
   Distance to crack from toe of slope..................................................(SUMKN + Kn+1)  =   130.00 m



Solution number  1    Crack number  7       (Lower limit)
   Factor of Safety.................................................................................(SF)  =   1.0038
   Weight of failed wedge between cracks  6 and  7...................................................(W)  =   409.18 kN
   Total area of the failure plane, of unit depth, between cracks  6 and  7.........................(At)  =     1.30 sq m
   Total uplift force due to water pressure acting on the failure plane between cracks  6 and  7.....(U)  =    92.91 kN
   Force applied to the failed wedge by the water in crack  7........................................(V)  =  1033.40 kN
   Resisting force due to tensile strength across the potential crack  7.............................(Y)  =  1016.04 kN
   Horizontal distance between cracks  6 and  7.................................................(Kn+1)  =     1.30 m
   Depth of crack  7 below surface..............................................................(Zn+1)  =    14.51 m
   Distance to crack from toe of slope..................................................(SUMKN + Kn+1)  =   131.30 m

   Case D1(a) - HW > B ie.  26.00 >   11.49


Solution number  1    Crack number  7       (Upper limit)
   Factor of Safety.................................................................................(SF)  =   1.0038
   Weight of failed wedge between cracks  6 and  7...................................................(W)  =   409.18 kN
   Total area of the failure plane, of unit depth, between cracks  6 and  7.........................(At)  =     1.30 sq m
   Total uplift force due to water pressure acting on the failure plane between cracks  6 and  7.....(U)  =    92.91 kN
   Force applied to the failed wedge by the water in crack  7........................................(V)  =  1033.40 kN
   Resisting force due to tensile strength across the potential crack  7.............................(Y)  =  1016.04 kN
   Horizontal distance between cracks  6 and  7.................................................(Kn+1)  =     1.30 m
   Depth of crack  7 below surface..............................................................(Zn+1)  =    14.51 m
   Distance to crack from toe of slope..................................................(SUMKN + Kn+1)  =   131.30 m

Invalid Case - Kn+1 is greater than (H1+H2)cot(beta)-Acot(beta)
               Factor of Safety (of remaining wedge) =  2.1207

Completion of run #  1 (Total of  3 runs were requested)
```

```
                         ****************************************************
                         *                                                  *
                         *                      MBPSSF                      *
                         *      Multiple Block Plane Shear Slope Failure    *
                         *                                                  *
                         ****************************************************

 Testing the program *****  Base Case ********


 Geometric Data
                 Height of the upper slope............................(H1)  =     6.00 m
                 Height of the lower slope............................(H2)  =    20.00 m
                 Height of the water table............................(Hw)  =    26.00 m
                 Bench width..........................................(Xb)  =    12.00 m
                 Angle of the upper slope with the horizontal........(A11)  =    60.00 deg
                 Angle of the lower slope with the horizontal........(A12)  =    70.00 deg
                 Angle of the failure plane with the horizontal.....(Beta)  =     5.00 deg
                 Incremental horizontal distance...................(Delta)  =   0.1000 m


 Material Properties
                 Tensile strength of the rock..........................(T)  =   70.000 kPa
                 Effective cohesion on the failure surface.............(C)  =    7.000 kPa
                 Density of rock in the failed wedge...............(Gamma)  =   21.600 kN/m3
                 Density of water.................................(Gammaw)  =    9.810 kN/m3
                 Effective angle of friction on the failure plane....(Phi)  =    8.000 deg


********************************************************************************
Run #  2     Type of Analysis: Probabilistic (option 1)
********************************************************************************

 The set of parameters to be used in this run will be selected by MBPSSF.
The selection will be made randomly from normal distributions

 Parameter     Mean Value      Standard Deviation      Value Generated from Normal Distribution
 _________     __________      __________________      ________________________________________

   Beta           5.00               0.200                              5.32
     T          70.000               0.500                             70.087
     C           7.000               0.500                              6.849
    Phi          8.00                0.100                             8.02

 Solution number  1    Crack number  1       (Lower limit)
   Factor of Safety..............................................................(SF)  =     0.9901
   Weight of failed wedge between cracks  0 and  1................................(W)  =  47937.63 kN
   Total area of the failure plane, of unit depth, between cracks  0 and  1......(At)  =    118.41 sq m
   Total uplift force due to water pressure acting on the failure plane between cracks  0 and  1.....(U)  =  21865.84 kN
   Force applied to the failed wedge by the water in crack  1.....................(V)  =   1106.96 kN
   Resisting force due to tensile strength across the potential crack  1..........(Y)  =   1052.90 kN
   Horizontal distance between cracks  0 and  1...............................(Kn+1)  =    117.90 m
   Depth of crack  1 below surface............................................(Zn+1)  =     15.02 m
   Distance to crack from toe of slope................................(SUMKN + Kn+1)  =    117.90 m

   Case A1(a) - HW > B ie.  26.00 >   10.98
```

```
Solution number  1    Crack number  1       (Upper limit)
  Factor of Safety..................................................................................(SF)  =    1.0100
  Weight of failed wedge between cracks  0 and  1....................................................(W)  =  51355.10 kN
  Total area of the failure plane, of unit depth, between cracks  0 and  1..........................(At)  =    129.36 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  0 and  1......(U)  =  23424.65 kN
  Force applied to the failed wedge by the water in crack  1.........................................(V)  =    962.45 kN
  Resisting force due to tensile strength across the potential crack  1..............................(Y)  =    981.77 kN
  Horizontal distance between cracks  0 and  1....................................................(Kn+1)  =    128.80 m
  Depth of crack  1 below surface.................................................................(Zn+1)  =     14.01 m
  Distance to crack from toe of slope.....................................................(SUMKN + Kn+1)  =    128.80 m

Invalid Case - Kn+1 is greater than (H1+H2)cot(beta)-Acot(beta)
               Factor of Safety (of remaining wedge) =  2.0031

Completion of run #  2 (Total of  3 runs were requested)
```

```
                    ****************************************************
                    *                                                  *
                    *                     MBPSSF                       *
                    *      Multiple Block Plane Shear Slope Failure    *
                    *                                                  *
                    ****************************************************

Testing the program *****  Base Case ********

Geometric Data
              Height of the upper slope...........................(H1)   =     6.00 m
              Height of the lower slope...........................(H2)   =    20.00 m
              Height of the water table...........................(Hw)   =    26.00 m
              Bench width.........................................(Xb)   =    12.00 m
              Angle of the upper slope with the horizontal........(Ai1)  =    60.00 deg
              Angle of the lower slope with the horizontal........(Ai2)  =    70.00 deg
              Angle of the failure plane with the horizontal.....(Beta)  =     5.00 deg
              Incremental horizontal distance..................(Delta)  =   0.1000 m


Material Properties
              Tensile strength of the rock.........................(T)   =   70.000 kPa
              Effective cohesion on the failure surface............(C)   =    7.000 kPa
              Density of rock in the failed wedge..............(Gamma)   =   21.600 kN/m3
              Density of water................................(Gammaw)   =    9.810 kN/m3
              Effective angle of friction on the failure plane....(Phi)  =    8.000 deg


*****************************************************************************
Run #  3     Type of Analysis: Probabilistic (option 1)
*****************************************************************************

 The set of parameters to be used in this run will be selected by MBPSSF.
The selection will be made randomly from normal distributions

 Parameter     Mean Value     Standard Deviation     Value Generated from Normal Distribution
 _________     __________     __________________     ________________________________________

   Beta           5.00             0.200                           4.95
    T            70.000            0.500                          69.251
    C             7.000            0.500                           7.060
    Phi           8.00             0.100                           8.05

 Solution number  1    Crack number  1       (Lower limit)
   Factor of Safety..........................................................................(SF)  =     0.9901
   Weight of failed wedge between cracks  0 and  1...........................................(W)   =  40962.38 kN
   Total area of the failure plane, of unit depth, between cracks  0 and  1..................(At)  =     96.26 sq m
   Total uplift force due to water pressure acting on the failure plane between cracks  0 and  1.....(U)  =  18673.32 kN
   Force applied to the failed wedge by the water in crack  1................................(V)   =   1536.48 kN
   Resisting force due to tensile strength across the potential crack  1.....................(Y)   =   1225.65 kN
   Horizontal distance between cracks  0 and  1...........................................(Kn+1)  =     95.90 m
   Depth of crack  1 below surface........................................................(Zn+1)  =     17.70 m
   Distance to crack from toe of slope.............................................(SUMKN + Kn+1)  =     95.90 m

   Case Ai(a) - HW > B ie.  26.00 >    8.30
```

```
Solution number  1    Crack number  1       (Upper limit)
  Factor of Safety.................................................................................(SF)  =     1.0098
  Weight of failed wedge between cracks  0 and  1...................................................(W)  =   43333.73 kN
  Total area of the failure plane, of unit depth, between cracks  0 and  1.........................(At)  =     102.58 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  0 and  1.....(U)  =   19754.33 kN
  Force applied to the failed wedge by the water in crack  1........................................(V)  =    1443.25 kN
  Resisting force due to tensile strength across the potential crack  1.............................(Y)  =    1187.89 kN
  Horizontal distance between cracks  0 and  1...................................................(Kn+1)  =     102.20 m
  Depth of crack  1 below surface................................................................(Zn+1)  =      17.15 m
  Distance to crack from toe of slope.....................................................(SUMKN + Kn+1)  =     102.20 m


Solution number  1    Crack number  2       (Lower limit)
  Factor of Safety.................................................................................(SF)  =     0.9924
  Weight of failed wedge between cracks  1 and  2...................................................(W)  =    3857.48 kN
  Total area of the failure plane, of unit depth, between cracks  1 and  2.........................(At)  =      10.74 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  1 and  2.....(U)  =     854.85 kN
  Force applied to the failed wedge by the water in crack  2........................................(V)  =    1291.61 kN
  Resisting force due to tensile strength across the potential crack  2.............................(Y)  =    1123.75 kN
  Horizontal distance between cracks  1 and  2...................................................(Kn+1)  =      10.70 m
  Depth of crack  2 below surface................................................................(Zn+1)  =      16.23 m
  Distance to crack from toe of slope.....................................................(SUMKN + Kn+1)  =     112.90 m

  Case D1(a) - HW > B ie.  26.00 >    9.77

Solution number  1    Crack number  2       (Upper limit)
  Factor of Safety.................................................................................(SF)  =     1.0064
  Weight of failed wedge between cracks  1 and  2...................................................(W)  =    3962.55 kN
  Total area of the failure plane, of unit depth, between cracks  1 and  2.........................(At)  =      11.04 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  1 and  2.....(U)  =     877.41 kN
  Force applied to the failed wedge by the water in crack  2........................................(V)  =    1287.47 kN
  Resisting force due to tensile strength across the potential crack  2.............................(Y)  =    1121.95 kN
  Horizontal distance between cracks  1 and  2...................................................(Kn+1)  =      11.00 m
  Depth of crack  2 below surface................................................................(Zn+1)  =      16.20 m
  Distance to crack from toe of slope.....................................................(SUMKN + Kn+1)  =     113.20 m


Solution number  1    Crack number  3       (Lower limit)
  Factor of Safety.................................................................................(SF)  =     0.9925
  Weight of failed wedge between cracks  2 and  3...................................................(W)  =    2504.80 kN
  Total area of the failure plane, of unit depth, between cracks  2 and  3.........................(At)  =       7.33 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  2 and  3.....(U)  =     559.57 kN
  Force applied to the failed wedge by the water in crack  3........................................(V)  =    1189.00 kN
  Resisting force due to tensile strength across the potential crack  3.............................(Y)  =    1078.19 kN
  Horizontal distance between cracks  2 and  3...................................................(Kn+1)  =       7.30 m
  Depth of crack  3 below surface................................................................(Zn+1)  =      15.57 m
  Distance to crack from toe of slope.....................................................(SUMKN + Kn+1)  =     120.50 m

  Case D1(a) - HW > B ie.  26.00 >   10.43

Solution number  1    Crack number  3       (Upper limit)
  Factor of Safety.................................................................................(SF)  =     1.0061
  Weight of failed wedge between cracks  2 and  3...................................................(W)  =    2572.02 kN
  Total area of the failure plane, of unit depth, between cracks  2 and  3.........................(At)  =       7.53 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  2 and  3.....(U)  =     574.26 kN
  Force applied to the failed wedge by the water in crack  3........................................(V)  =    1186.36 kN
  Resisting force due to tensile strength across the potential crack  3.............................(Y)  =   1076.99 kN
  Horizontal distance between cracks  2 and  3...................................................(Kn+1)  =      7.50 m
  Depth of crack  3 below surface................................................................(Zn+1)  =     15.55 m
  Distance to crack from toe of slope.....................................................(SUMKN + Kn+1)  =    120.70 m


Solution number  1    Crack number  4        (Lower limit)
  Factor of Safety.....................................................................................(SF)  =    0.9924
  Weight of failed wedge between cracks  3 and  4.......................................................(W)  =   1656.25 kN
  Total area of the failure plane, of unit depth, between cracks  3 and  4.............................(At)  =      5.02 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  3 and  4.....(U)  =    372.19 kN
  Force applied to the failed wedge by the water in crack  4............................................(V)  =   1121.25 kN
  Resisting force due to tensile strength across the potential crack  4.................................(Y)  =   1047.02 kN
  Horizontal distance between cracks  3 and  4.......................................................(Kn+1)  =      5.00 m
  Depth of crack  4 below surface....................................................................(Zn+1)  =     15.12 m
  Distance to crack from toe of slope.........................................................(SUMKN + Kn+1)  =    125.70 m

  Case D1(a) - HW > B ie.  26.00 >   10.88

Solution number  1    Crack number  4        (Upper limit)
  Factor of Safety.....................................................................................(SF)  =    1.0023
  Weight of failed wedge between cracks  3 and  4.......................................................(W)  =   1688.90 kN
  Total area of the failure plane, of unit depth, between cracks  3 and  4.............................(At)  =      5.12 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  3 and  4.....(U)  =    379.41 kN
  Force applied to the failed wedge by the water in crack  4............................................(V)  =   1119.96 kN
  Resisting force due to tensile strength across the potential crack  4.................................(Y)  =   1046.42 kN
  Horizontal distance between cracks  3 and  4.......................................................(Kn+1)  =      5.10 m
  Depth of crack  4 below surface....................................................................(Zn+1)  =     15.11 m
  Distance to crack from toe of slope.........................................................(SUMKN + Kn+1)  =    125.80 m


Solution number  1    Crack number  5        (Lower limit)
  Factor of Safety.....................................................................................(SF)  =    0.9997
  Weight of failed wedge between cracks  4 and  5.......................................................(W)  =   1130.91 kN
  Total area of the failure plane, of unit depth, between cracks  4 and  5.............................(At)  =      3.51 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  4 and  5.....(U)  =    255.16 kN
  Force applied to the failed wedge by the water in crack  5............................................(V)  =   1075.50 kN
  Resisting force due to tensile strength across the potential crack  5.................................(Y)  =   1025.44 kN
  Horizontal distance between cracks  4 and  5.......................................................(Kn+1)  =      3.50 m
  Depth of crack  5 below surface....................................................................(Zn+1)  =     14.81 m
  Distance to crack from toe of slope.........................................................(SUMKN + Kn+1)  =    129.30 m

  Case D1(a) - HW > B ie.  26.00 >   11.19

Solution number  1    Crack number  5        (Upper limit)
  Factor of Safety.....................................................................................(SF)  =    0.9997
  Weight of failed wedge between cracks  4 and  5.......................................................(W)  =   1130.91 kN
  Total area of the failure plane, of unit depth, between cracks  4 and  5.............................(At)  =      3.51 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  4 and  5.....(U)  =    255.16 kN
  Force applied to the failed wedge by the water in crack  5............................................(V)  =   1075.50 kN
  Resisting force due to tensile strength across the potential crack  5.................................(Y)  =   1025.44 kN
  Horizontal distance between cracks  4 and  5.......................................................(Kn+1)  =      3.50 m
  Depth of crack  5 below surface....................................................................(Zn+1)  =     14.81 m
  Distance to crack from toe of slope.........................................................(SUMKN + Kn+1)  =    129.30 m
```

```
Solution number  1    Crack number  6       (Lower limit)
  Factor of Safety.................................................................................(SF)  =     0.9944
  Weight of failed wedge between cracks  5 and  6...................................................(W)  =   762.24 kN
  Total area of the failure plane, of unit depth, between cracks  5 and  6.........................(At)  =     2.41 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  5 and  6.....(U)  =   172.51 kN
  Force applied to the failed wedge by the water in crack  6........................................(V)  =  1045.54 kN
  Resisting force due to tensile strength across the potential crack  6.............................(Y)  =  1011.05 kN
  Horizontal distance between cracks  5 and  6...................................................(Kn+1)  =     2.40 m
  Depth of crack  6 below surface................................................................(Zn+1)  =    14.60 m
  Distance to crack from toe of slope....................................................(SUMKN + Kn+1)  =   131.70 m

  Case D1(a) - HW > B ie.  26.00 >   11.40

Solution number  1    Crack number  6       (Upper limit)
  Factor of Safety.................................................................................(SF)  =     0.9944
  Weight of failed wedge between cracks  5 and  6...................................................(W)  =   762.24 kN
  Total area of the failure plane, of unit depth, between cracks  5 and  6.........................(At)  =     2.41 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  5 and  6.....(U)  =   172.51 kN
  Force applied to the failed wedge by the water in crack  6........................................(V)  =  1045.54 kN
  Resisting force due to tensile strength across the potential crack  6.............................(Y)  =  1011.05 kN
  Horizontal distance between cracks  5 and  6...................................................(Kn+1)  =     2.40 m
  Depth of crack  6 below surface................................................................(Zn+1)  =    14.60 m
  Distance to crack from toe of slope....................................................(SUMKN + Kn+1)  =   131.70 m


Solution number  1    Crack number  7       (Lower limit)
  Factor of Safety.................................................................................(SF)  =     1.0021
  Weight of failed wedge between cracks  6 and  7...................................................(W)  =   533.41 kN
  Total area of the failure plane, of unit depth, between cracks  6 and  7.........................(At)  =     1.71 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  6 and  7.....(U)  =   120.97 kN
  Force applied to the failed wedge by the water in crack  7........................................(V)  =  1024.57 kN
  Resisting force due to tensile strength across the potential crack  7.............................(Y)  =  1000.86 kN
  Horizontal distance between cracks  6 and  7...................................................(Kn+1)  =     1.70 m
  Depth of crack  7 below surface................................................................(Zn+1)  =    14.45 m
  Distance to crack from toe of slope....................................................(SUMKN + Kn+1)  =   133.40 m

  Case D1(a) - HW > B ie.  26.00 >   11.55

Solution number  1    Crack number  7       (Upper limit)
  Factor of Safety.................................................................................(SF)  =     1.0021
  Weight of failed wedge between cracks  6 and  7...................................................(W)  =   533.41 kN
  Total area of the failure plane, of unit depth, between cracks  6 and  7.........................(At)  =     1.71 sq m
  Total uplift force due to water pressure acting on the failure plane between cracks  6 and  7.....(U)  =   120.97 kN
  Force applied to the failed wedge by the water in crack  7........................................(V)  =  1024.57 kN
  Resisting force due to tensile strength across the potential crack  7.............................(Y)  =  1000.86 kN
  Horizontal distance between cracks  6 and  7...................................................(Kn+1)  =     1.70 m
  Depth of crack  7 below surface................................................................(Zn+1)  =    14.45 m
  Distance to crack from toe of slope....................................................(SUMKN + Kn+1)  =   133.40 m

Invalid Case - Kn+1 is greater than (H1+H2)cot(beta)-Acot(beta)
               Factor of Safety (of remaining wedge) =  2.1590

Completion of run #  3 (Total of  3 runs were requested)

Finish
```

Volume

3

7 of 12

~~Confidential~~ declassified

COAL MINING RESEARCH CENTRE

MULTIPLE BLOCK PLANE SHEAR SLOPE FAILURE
PART III: SENSITIVITY ANALYSES, CASE HISTORIES AND CONCLUSIONS

by
K. BARRON, B. STIMPSON and K. KOSAR
CMRC REPORT 84/31-C MARCH 1985

FINAL REPORT - VOLUME III

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CONTENTS

PAGE

1. Introduction 1

2. Sensitivity analyses 1

2.1 Base case 1 - Sensitivities 4

2.1.1 Effect of variations of H_2 4
2.1.2 Effect of variations of i_1 and i_2 7
2.1.3 Effect of variations of H_w (from 0 m to 26 m) 7
2.1.4 Effect of variations of tensile strength T 8
2.1.5 Effect of variations of c and ϕ. 8
2.1.6 Effect of variations of failure plane angle 11

2.2 Base case 2 - Sensitivities 11
2.3 Summary of conclusions and their mining implications 15

3. Case histories 17

3.1 Landslides at Folkstone Warren 17
3.2 Progressive failure caused by deep excavation in Oxford clay 33
3.3 Slope failure - Highvale (1983) 49
3.4 Slope failure - Highvale (1984) 71

3.4.1 Case history #4 Slope failure - Highvale (1984) 71
3.4.2 Surface mapping and sampling 75
3.4.3 Laboratory shear testing 75
3.4.4 Ground water information 78
3.4.5 MBPSSF analysis 78
3.4.6 Probability of failure extending beyond x_1 metres (H_w = 7.0 m) 80
3.4.7 Potential effect of drainage 80

4. Conclusions 85

5. References 86

6. Acknowledgements 87

FIGURES

		PAGE
FIGURE 1	Base case geometries	3
FIGURE 2	General site plan	19
FIGURE 3	Main types of landslide occurring	19
FIGURE 4	Location of wells in the Chalk inland	21
FIGURE 5	Ground-water conditions in the slipped masses and in the adjacent Chalk	21
FIGURE 6	Typical stress-displacement curves for Gault, sample 2	23
FIGURE 7	Results of drained shear tests on Gault, sample 2	23
FIGURE 8	Suggested mechanism of retrogression	25
FIGURE 9	Ground-water conditions in the slipped masses and in the adjacent Chalk	28
FIGURE 10	Simplified seaction for MBPSSF analysis	28
FIGURE 11	Planer cutting northwards along the east face of Saxon pit; the major joints can be seen intersecting the slightly darker Lower Oxford Clay in the foreground	34
FIGURE 12	Plan showing successive faces of excavation, major joints in the Oxford Clay and layout of instrumentation	34
FIGURE 13	Centre line section normal to the face showing position of successive faces and major joints, geology and instrumentation	35
FIGURE 14	Orientation and frequency of major joints at Saxon pit	35
FIGURE 15	Variation with depth of the geotechnical properties of the Oxford Clay and Kellaways Beds	37
FIGURE 16	Typical shear stress-displacement curves and strength envelope for direct drained shear tests on Lower Oxford Clay specimens sheared parallel to the bedding	37
FIGURE 17	Variation of piezometric levels with time on the centre line of the face showing the relationship with face position.	39
FIGURE 18	(a) Variation of total horizontal surface strain with distance from advancing face (derived from Fig. 20(a)), (b) interpretation of the surface strain distribution derived from the observations on point 28	39
FIGURE 19	Distribution of shear stress and horizontal strain during propagation of shear band	42
FIGURE 20	Simplified section for MBPSSF analysis	48
FIGURE 21	Plan of failure zone	50
FIGURE 22	Highvale Mine Pit 03, Cut 7 Highwall Failure Study, Borehole Location Plan	51
FIGURE 23	Highvale Mine Pit 03, Cut 7 Highwall Failure Study, Section 2-2	51
FIGURE 24	Highvale Mine Pit 03, Cut 7 Highwall Failure Study, Effective Stress Mohr Envelope for Bentonitic Clay (Soil #4) Hole No. HV-83-406 Sample No. U-10 (14.7 m to 14.9 m)	54

FIGURES (Continued)

PAGE

FIGURE 25 MBPSSF Analysis - Highvale 1983 - Deterministic solution 58
FIGURE 26 Individual probability of a crack occuring 66
FIGURE 27 Combined probability of a crack occuring 66
FIGURE 28 Distribution curves for crack positions - 95% probability 67
FIGURE 29 Probability of failure extending beyond X_i metres 70
FIGURE 30 Pit 03 Highvale Mine April 1/84 72
FIGURE 31 Highwall slide Highvale Mine Pit 3 April 1984 76
FIGURE 32 Four cross sections chosen for analysis 77
FIGURE 33 Observed and calculated extent of cracking 79
FIGURE 34 Probability of cracking beyond X_i metres - H_w varied - Section 5 + 70 81
FIGURE 35 Probability of cracking extending beyond X_i metres from the toe 82
FIGURE 36 Probability of failure extending beyond specific distances versus H_w - Section 5 + 70 83

FIGURE A1.1 Nomenclature 89
FIGURE A1.2 True dip frequency distribution 94
FIGURE A1.3 Probability that given value > X_{im} - True dip 94
FIGURE A1.4 Apparent dip - East wall 95
FIGURE A1.5 Apparent dip - South wall 95
FIGURE A2.1 Highvale Mine Pit 03, Cut 7 Highwall failure study. Effective stress Mohr envelope for Bentonitic clay (Soil #4) Hole No. HV-83-406 Sample No. U-10 (14.7 m to 14.9 m) 99
FIGURE A2.2 Shear test results - all data 105
FIGURE A2.3 Distribution curve for μ - all data - peak 105
FIGURE A2.4 Distribution curve for c - all data - peak 106
FIGURE A3.1 Peak strengths on clay seam Site 1 111
FIGURE A3.2 Peak strengths on clay near coal contact Site 2 112
FIGURE A3.3 Residual strengths on clay seam Site 1 113
FIGURE A4.1 Location of piezometer installations. Piezometers installed in rotary holes are completed in coal seam number 6 (except CHV83-2, completed in seam number 1). Piezometers installed in augered holes are completed in the overburden sandstone 115
FIGURE A4.2 Piezometric surface cross section FF 118
FIGURE A4.3 Piezometric surface cross section AA 119
FIGURE A4.4 Estimated limits of phraetic line near the pit 122
FIGURE A5.1 Observed and calculated extent of cracking 129
FIGURE A5.2 Probability of cracking extending beyond X_i metres from the toe 132
FIGURE A5.3 Probability of cracking beyond X_i metres - H_w varied - Section 5 + 70 141
FIGURE A5.4 Probability of failure extending beyond specific distances versus H_w - Section 5 + 70 142

TABLES

		PAGE
Table 1	Base Case deterministic solutions	4
Table 2	Base Case 1 - Effect of Variation of H_2 (H_2 from 10 m to 50 m)	5
Table 3	Base Case 1 - Variation of i_1 and i_2 (From 60/70° to 30/30°)	5
Table 4	Base Case 1 - Variation of H_w (From 0 m to 26 m)	5
Table 5	Base Case 1 - Effect of Variation of T (From 0 to 70 kPa)	9
Table 6	Base Case 1 - Effect of Variation of c and ϕ (Simultaneous Variation)	9
Table 7	Base Case 1 - Effect of Variation of β (From 0° to 50°)	9
Table 8	Base Case 2 - Variation of H_2	12
Table 9	Base Case 2 - Variation of i_1/i_2	12
Table 10	Base Case 2 - Variation of H_w	12
Table 11	Base Case 2 - Variation of T kPa	13
Table 12	Base Case 2 - Variation of C & ϕ	13
Table 13	Base Case 2 - Variation of β	13
Table 14	MBPSSF - Multiple Block Plane Shear Slope Failure Test Case #3 - Folkestone	30
Table 15	MBPSSF - Multiple Block Plane Shear Slope Failure Test Case #3 - Folkestone	31
Table 16	MBPSSF - Multiple Block Plane Shear Slope Failure Test Case #3 - Folkestone Case 1: H_w = 300 ft. Case 2: H_w = 350 ft.	32
Table 17	MBPSSF - Multiple Block Plane Shear Slope Failure Test Case #3 - Oxford	45
Table 18	MBPSSF - Multiple Block Plane Shear Slope Failure Test Case #3 - Oxford	46
Table 19	MBPSSF - Multiple Block Plane Shear Slope Failure Test Case #3 - Oxford	47
Table 20	Summary of Physical Properties of Major Stratigraphic Units	54
Table 21	Highvale (1983) - Variation of H_w - Deterministic Solutions	59
Table 22	Highvale (1983) - H_w = 8.27 m - Probabilistic Solutions	62
Table 23	Highvale (1983) - H_w = 8.27 m - Probabilistic Solutions	64
Table 24	Range of crack positions at 95% probability level	68

TABLES (Continued)

PAGE

Table A1 Dip of Bentonitic clay band - Pit 03 - Highvale 92
Table A2 Histogram frequency data 93
Table A3 Shear test results - data set 1 100
Table A4 Shear test results - data set 2 101
Table A5 Shear test results - data set 3 102
Table A6 Shear test results - all data 104
Table A7 Clay sample from Site #1 - Peak Strengths, Bulk Densities and Moisture contents 109
Table A8 Clay sample from Site #2 - Peak Strengths, Bulk Densities and Moisture contents 110
Table A9 Clay sample from Site #1 - Residual Strengths, Bulk Densities and Moisture contents 110
Table A10 Summary of Highwall Stability Project Piezometer Installation Information 116
Table A11 Water Level Measurements, Pit 03 Piezometers - in sandstone overburden 117
Table A12 Sandstone Piezometers 120
Table A13 Section 3+70, Hw=7.0 m - Probabslistic Analyses 124
Table A14 Section 5+70, Hw=7.0 m - Probabalistic Analyses 125
Table A15 Section 6+70, Hw=7.0 m - Probabalistic Analyses 126
Table A16 Section 8+40, Hw=7.0 m - Probabalistic Analyses 127
Table A17 Probability of cracking extending beyond X_i metres from the toe (H_w = 7.0 m) 130
Table A18 Section 5+70 Hw = 1.5 m 134
Table A19 Section 5+70 Hw = 2 m 135
Tabel A20 Section 5+70 Hw = 3.0 m 136
Table A21 Section 5+70 Hw = 4.0 m 137
Table A22 Section 5+70 Hw = 5.0 m 138
Table A23 Section 5+70 Hw = 8.0 m 139
Table A24 Probability of cracking extending beyond X_i metres - Section 5 + 70 - H_w variation 140

APPENDICES

Appendix 1: Derivation of normal distribution curve from histogram data

Appendix 2: Determination of the frequency distribution of the cohesion and angle of friction

Appendix 3: Direct shear box tests on clay samples from Highvale Mine, Alberta

Appendix 4: Ground Water Information - Pit 03 - October 1983 to April 1984

Appendix 5: MBPSSF Analysis - Highvale (1984)

1. Introduction

Volume 1 of the final report developed the theoretical analysis of pit slope failure by the mode called "Multiple block plane shear slope failure" (MBPSSF). Volume 2 of this final report describes and lists the computer program developed to perform the stability analysis for multiple block plane shear slope failure. This program may be run in the "deterministic mode" using mean values of the input parameters or alternatively it may be run in the "probabalistic mode" whereby the mean and standard deviation of the geotechnical parmeters are input and, using a random number generator, Monte Carlo methods are used to determine the probabilities of failure (by say, running 99 cases).

This volume III of the final report addresses the sensitivity of this failure mechanism to variations in the input parameters. It details four case histories (3 from the literature and one field documentation) and applies the MBPSSF analysis to these cases, using both deterministic and probabalistic solutions, as deemed appropriate. (Note: originally the contract called for two field case studies. However during the contract period this type of failure did not re-occur at one of the two mines under consideration; consequently this case study could not be performed. With the agreement of the scientific authority it was decided to replace this field study with 3 case histories taken from the literature. The field case study at the other Alberta mine was carried out as planned).

Finally the results of these studies are discussed, conclusions drawn with respect to control methods and the effects of deeper mining (higher pit walls).

2. Sensitivity Analyses

In order to establish the sensitivities of the pit slope stability to variations in the input parameters, two base case studies were established.

For both base cases the initial geometry was kept the same, as illustrated in Figure 1 and listed below:-

Geometry: Base cases 1 and 2

$H_1 = 6$ m
$H_2 = 20$ m
$H_w = 26$ m (full height)
$x = 12$ m
$i_1 = 60^o$
$i_2 = 70^o$
$\beta = 5^o$

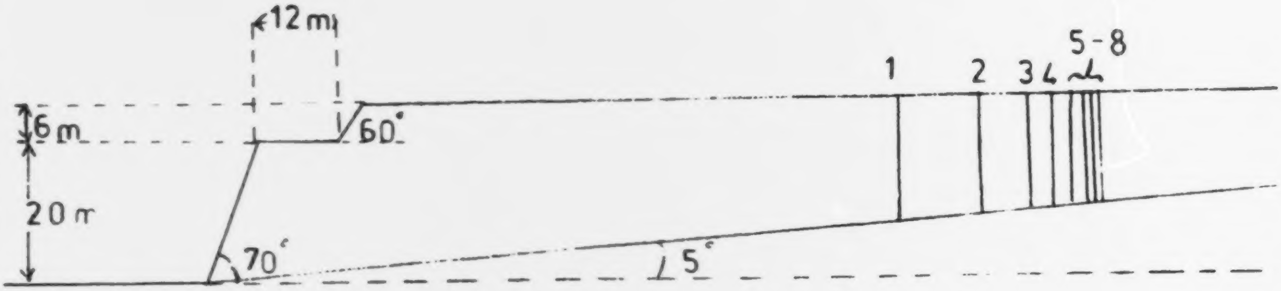
also the unit weights for both base cases were kept constant at

$\gamma^R = 21.6$ kN/m^3
$\gamma^w = 9.81$ kN/m^3
as was the tensile strength
$T = 70$ kPa

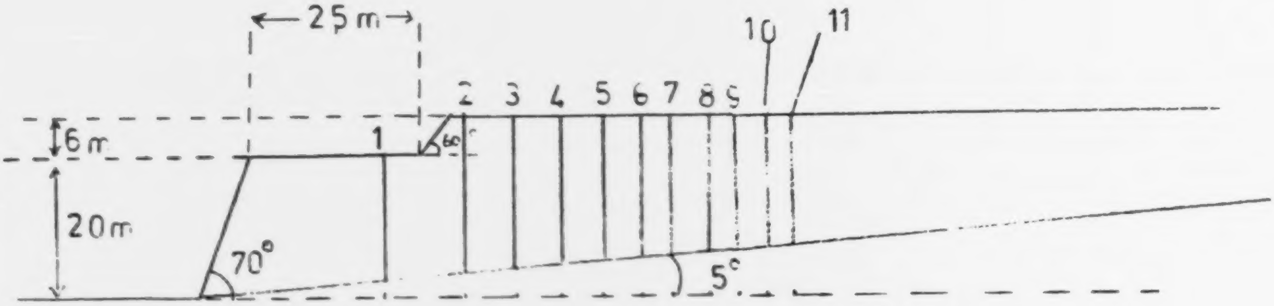
The cohesion and angle of friction were different for the two base cases; as was the bench width x:

Base case 1: $c = 7$ kPa, $\phi = 8^o$, $x = 12$ m
Base case 2: $c = 25$ kPa, $\phi = 20^o$, $x = 25$ m

These two base cases were run, in the deterministic mode, and the positions of the cracks for each case are given in Table 1 below and illustrated in Figure 1.


12m
6m
20m
60°
70°
5°
1
2
3
4
5-8

(A).BASE CASE1


25m
6m
20m
1
60°
70°
5°
2
3
4
5
6
7
8
9
10
11

(B).BASE CASE 2

FIG 1 : BASE CASE GEOMETRIES

TABLE 1: BASE CASE DETERMINISTIC SOLUTIONS

Crack No. CASE	1	2	3	4	5	6	7	8	9	10	11	
						Distance from toe - metres						
BASE CASE 1	102	114.6	120.9	125.1	128.0	129.9	131.2	132.1		STABLE		
BASE CASE 2	27.5	39.1	46.4	53.1	59.2	64.8	69.4	74.7	79.2	83.2	86.9	STABLE

The first base case was chosen so that the first crack occurred well back in the slope crest, so that the face geometry would have little influence on the crack formation.

In contrast the second base case was chosen so that the first crack occurred in the bench and the effects of face geometry would be included.

These two base cases formed the basis for sensitivity analyses in which the effects of varying each parameter in turn were examined.

2.1 - Base Case 1 - Sensitivities

2.1.1. Effect of variations of H_2

The value of H_2 was varied from 10 m to 50 m, keeping all other parameters at the values given for base case 1. Table 2 summarises the number of cracks and their distance from the toe.

The following conclusion can be drawn:-

(1) As H_2 increases so the total extent of cracking decreases, as does the number of cracks.

(2) At a low H_2 value the whole wedge fails to the outcrop. Then as H_2 increases the whole wedge does not fail but cracks up into a large

TABLE 2: BASE CASE 1 - EFFECT OF VARIATION OF H_2 (H_2 from 10 m to 50 m)

H_2 m	Distance of crack from toe - metres Crack No. 1	2	3	4	5	6	7	8	9	10	11	12	13	14
10	WHOLE SLOPE WEDGE FAILS TO OUTCROP AT 182.9 m S.F = 0.415													
20 (base)	102	114.6	120.9	125.1	128.0	129.9	131.2	132.1		STABLE S.F. = 2.12				
30	38.1	44.2	48.0	50.7	52.5					STABLE S.F = 1.84				
40	21.0	25.2								STABLE S.F = 1.78				
50	15.5									STABLE S.F = 1.74				

TABLE 3: BASE CASE 1 - VARIATION OF i_1 and i_2 (From 60/70° to 30/30°)

i_1	i_2	Distance of crack from toe - metres Crack No. 1	2	3	4	5	6	7	8	9	10	11	12	13	14
60° (base)	70°	102	114.6	120.9	125.1	128.0	129.9	131.2	132.1		STABLE S.F = 2.12				
50°	60°	100.5	113.5	120.2	124.6	127.7	129.7	131.1			STABLE S.F = 2.12				
40°	50°	98.6	112.0	119.2	124.0	127.2	129.4	130.9	131.9	132.6	STABLE S.F = 2.12				
30°	40°	95.9	110.1	117.9	123.1	126.6	129.0	130.6	131.7		STABLE S.F = 2.12				
30°	30°	92.3	107.4	116.1	121.9	125.8	128.5	130.2	131.5	132.3	STABLE S.F = 2.12				

TABLE 4: BASE CASE 1 - VARIATION OF H_w (From 0 m to 26 m)

H_w m	Distance of crack from toe - metres Crack No. 1	2	3	4	5	6	7	8	9	10	11	12	13	14
0	NO CRACKS - STABLE S.F = 1.91													
5	NO CRACKS - STABLE S.F = 1.79													
10	NO CRACKS - STABLE S.F = 1.68													
15	NO CRACKS - STABLE S.F = 1.57													
20	NO CRACKS - STABLE S.F = 1.47													
25	80.2	92.1	98.6	109.9	105.9	107.8	109.1	110.0		STABLE S.F = 2.06				
26 (base)	102	114.6	120.9	125.1	128.0	129.9	131.2	132.1		STABLE S.F = 2.12				

number of blocks. This number decreases with further increase of H_2.

(3) The distance between successive blocks becomes smaller as H_2 increases.

(4) Failure is very sensitive to H_2 (and by inference to H_1)

(5) OVERALL, IT MAY BE CONCLUDED THAT AS THE DEPTH OF OVERBURDEN INCREASES SO THE STABILITY OF THE SLOPE INCREASES. THIS IS THE ONLY MODE OF SLOPE FAILURE KNOWN TO THE AUTHORS WHEREBY SLOPE STABILITY INCREASES WITH INCREASING DEPTH OF OVERBURDEN.

This result may seem surprising at first, until it is realised that for the very shallow failure planes (low β) at least, the main resisting force is that due to internal friction which, of course, increases with the normal force. Consequently, as H_2 increases so does the normal force, and hence the resisting force increases giving greater stability. Clearly this must breakdown as β increases.

(Also it should be noted that H_w, the height of the water table above the toe, was kept constant. In practice this would be unlikely, a more likely effect would be for the depth of the water table below surface to perhaps remain constant. In such a case H_w would increase as H_2 increases and the higher water pressures would outweigh the increased frictional resistance and would reduce stability).

2.1.2 Effect of variation of i_1 and i_2

The values of i_1 and i_2 were simultaneously varied through the values shown in Table 3, keeping all other parameters at the base case 1 values. Table 3 summarises the number of cracks and their distances from the toe. The following conclusions may be drawn:

1. The stability is relatively insensitive to variations in i_1 and i_2. This is not surprising since in the base case the first crack occurs well back into this slope crest. Consequently, the changes in i_1 and i_2 have very little effect on the total volume or weight of the failing blocks and thus the forces remain virtually unchanged. This might not be the case when the first crack occurs, say, in the bench.

2.1.3 Effect of variations of H_w (from O m to 26 m)

The height of the water table, H_w, above the toe was varied from 0 m to the full pit height (26 m), keeping all other parameters at the base case 1 values. Table 4 summarises the results.

The following conclusions may be drawn:-

1. For low H_w values (0 - 20 m) the slope is stable; beyond this point the effects are dramatic. The next five meters extends the cracking from zero to 110 m beyond the toe. (indeed as will be shown later in base case 2, the change from zero effect to a dramatic effect is caused by even smaller changes in H_w)
2. Clearly stability is EXCEPTIONALLY SENSITIVE to H_w. This is not surprising since the water uplift forces represent the major disturbing force (particularly when β is low). Hence, once the slope is close to failure it will only take a very small increment of H_w to the destabilize the slope for a great distance.
3. It follows from this that DRAINAGE, if possible, offers potentially the best method of preventing slope failure.

2.1.4 Effect of variation of tensile strength T.

The values of tensile strength assumed for the rock were varied from 0 to 70 kPa, keeping all other parameters at the base case 1 values. Table 5 shows the results. The following conclusions may be drawn.

1. As expected an increase in T increases the stability of the slope. However, since T is usually very small or zero the overall effect will always be small and probably insignificant.
2. What is perhaps more interesting is the fact the the number of crack sets occuring initially increases with increase of T; the number of sets peaks and then diminishes with further increase of T. However, the total extent of cracking (distance of the last crack from the toe) decreases at T increases showing that the overall stability is also increasing. It is clear that the number of crack sets which may occur can vary considerably and is probably not important, since if the total wedge fails (ie. one crack at outcrop) as was the case for H_w = 10 m (Table 2) or if the wedge breaks up into 10 cracks sets (as with T = 20 kPa in table 5), the slope has still failed. What is more important is the total extent of cracking ie. the distance of the last crack from the toe.

2.1.5 Effect of variation of c and ϕ

The values of the peak cohesion, c, and the angle of internal friction, ϕ on the failure plane were simultaneously varied through the values given in table 6, all other parameters being kept constant at the base case values. The table 6 summarises the results from which the following conclusions may be drawn.

TABLE 5: BASE CASE 1 - EFFECT OF VARIATION OF T (from 0 to 70 kPa)

T kPa	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Distance of crack from toe - metres Crack No.													
0	180	209.6	227.3	239.9	249.3	256.4	261.9	266.3			STABLE S.F = 4.36			
10	171.9	199.5	216	227.9	236.7	243.4	248.5	252.5	255.7		STABLE S.F = 3.66			
20	162.9	188.3	203.3	214.1	222.0	228.0	232.5	236.0	238.8	241.0	STABLE S.F = 3.12			
70 (base)	102	114.6	120.9	128.1	128.	129.9	131.2	132.1			STABLE S.F = 2.12			

TABLE 6: BASE CASE ϕ - VARIATION OF c and ϕ (Simultaneous variation)

c kPa	ϕ	1	2	3	4	5	6	7	8	9	10	11	12	13	14
		Distance of crack from toe - metres Crack No.													
7 (base)	8	102	114.6	120.9	125.1	128.0	129.9	131.2	132.1			STABLE S.F = 2.12			
0	10	92.2	106.3	114.3	120.5	124.1	127.1	129.1				STABLE S.F. = 2.02			
10	15	30.3	44.2	55.3	65.0	73.5	80.9	87.4	93.2	98.2	102.5	106.3	109.6	112.5	115.1
												STABLE S.F = 3.73			
15	20							NO CRACKS - STABLE S.F = 2.90							
25	25							NO CRACKS - STABLE S.F = 3.96							

TABLE 7: BASE CASE 1 - EFFECT OF VARIATION OF β (From 0° to 50°)

β deg.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Distance of crack from toe - metres Crack No.													
0	36.5	58.7	80.9	103.1	125.3	147.5	169.7	192.9	214.1	236.3	250.5 TO INFINITY EACH SET 22.2 m APART			
5 (base)	102	114	120.9	125.1	128	129.9	131.2	132.1			STABLE S.F = 2.12			
10					WHOLE WEDGE FAILS - S.F = 0.583									
15					WHOLE WEDGE FAILS - S.F = 0.382									
30					WHOLE WEDGE FAILS - S.F = 0.163									
40					WHOLE WEDGE FAILS - S.F = 0.088									
50			PLANE CUTS BENCH - TREAT AS TWO SEPARATE SLOPES (BOTH WILL FAIL)											

1. Not surprisingly increasing c and ϕ increases the shear resistance and stability is increased.
2. As with variations in T, the number of crack sets occuring increases to a peak and then diminishes, but the total extent of the fracturing decreases with the increasing shear resistance.

2.1.6 Effect of Variation of failure plane angle β

β was varied from 0° to 50°, keeping all other parameters at the base case 1 values. Table 7 summarises the results from which the following conclusions may be drawn.

1. When β = 0, an infinite number of cracks occur which will extend back to infinity ! Whilst clearly this is not the case in practice it is a theoretically valid solution. In practice, either some changes in parameters with distance (such as water-table variations) or a collapsing of failed blocks back onto the adjacent deeper block could give a buttress toe load which might prevent further cracking. Nonetheless, as will be seen from the ensuing case histories, it is possible for cracking in practice to extend back into the crest for at least 5 times the total slope height.

   This theoretical, infinite, solution is obviously valid since, once cracking has gone beyond the crest when β = 0°, the forces on each successive block are identical and continuing retrogressive failure must theoretically occur.

   Note however that (a) this is not necessarily restricted to β = 0°, negative or even some small positive β values could also yield the same infinite result (b) if cracking does not extend beyond the crest, then regardless of the β values an infinite number of cracks cannot occur.

2.2 Base Case 2 - Sensitivities

A similar sensitivity analysis was carried out for base case 2, varying each of the parameters in turn. Tables 8 to 13 list the results of these analyses. Since many of the conclusions from this study are the same as for base case 1, they will not be re-iterated. Rather, a number of comments will be made where new conclusions or interesting points are revealed by this second base case. These comments are as follows:-

TABLE 8: BASE CASE - VARIATION OF H_2

Distance of crack from toe - metres

H_2 m	Crack No. 1	2	3	4	5	6	7	8	9	10	11	12	13	14
10	38.0	63.0	86.1	109	132.3	158.4	REMAINING WEDGE FAILS S.F = 0.66							
20 (base)	27.5	39.1	46.4	53.1	59.2	69.8	69.9	74.7	79.2	83.2	86.9		STABLE S.F. = 5.61	
30	14.2	20.4	26.1	31.4	STABLE - ANALYSIS TERMINATES WHEN TOE DISTANCE 10 x SLOPE HEIGHT									
40	12.2				STABLE - ANALYSIS TERMINATES WHEN TOE DISTANCE 10 x SLOPE HEIGHT									
50	12.2				STABLE - ANALYSIS TERMINATES WHEN TOE DISTANCE 10 x SLOPE HEIGHT									
60	12.2				STABLE - ANALYSIS TERMINATES WHEN TOE DISTANCE 10 x SLOPE HEIGHT									

TABLE 9: BASE CASE - VARIATION OF i_1 and i_2

Distance of crack from toe - metres

i_1	i_2	Crack No. 1	2	3	4	5	6	7	8	9	10	11	12	13	14
60° (base)	70°	27.5	39.1	46.4	53.1	59.2	64.8	69.9	74.7	79.2	83.2	86.9		STABLE	
50°	60°	28.3													
40°	50°	29.2			STABLE - ANALYSES TERMINATED AT 10 x SLOPE HEIGHT										
30°	40°	30.6	46.1	STABLE S.F. = 3.51											
30°	30°	33.5	55.0	STABLE S.F. = 3.57											

TABLE 10: BASE CASE - VARIATION OF H_w

Distance of crack from toe - metres

H_w m	Crack No. 1	2	3	4	5	6	7	8	9	10	11	12	13	14
26 (base)	27.5	39.1	26.4	53.1	59.2	64.8	69.9	74.7	79.2	83.2	86.9	STABLE S.F. = 5.61		
22.5	15.7	24.2	31.9		STABLE TERMINATES AT 10 x SLOPE HEIGHT									
20	9.1	13.3	17.1	20.6	23.9	26.9	29.7	STABLE - TERMINATES AT 10 x SLOPE HEIGHT						
17.5	NO SOLUTION - EXCEEDS 10 x SLOPE HEIGHT S.F. = 4.23													
15	NO SOLUTION - EXCEEDS 10 x SLOPE HEIGHT S.F. = 4.38													

TABLE 11: BASE CASE 2 - VARIATION OF T kPa

T kPa	Distance of crack from toe - metres Crack No. 1	2	3	4	5	6	7	8	9	10	11	12	13	14
60	30.0	44.4	53.0	6.8	68.0	74.7	80.7	86.4	91.5	96.4	100.8	104.9	STABLE S.F. = 5.74	
70 (Base)	27.5	39.1	26.4	53.1	59.2	64.8	69.9	74.7	79.2	83.2	86.9	STABLE S.F. = 5.61		
100	19.7	30.8		STABLE - EXCEEDS 10 x SLOPE HEIGHT										

TABLE 12: BASE CASE 2 - VARIATION OF c and ϕ

c kPa	α deg.	Distance of crack from toe - metres Crack No. 1	2	3	4	5	6	7	8	9	10	11	12	13	14
25 (base)	20	27.5	39.1	26.4	53.1	59.2	64.8	69.9	74.7	79.2	83.2	86.9	STABLE S.F. = 5.61		
18	23	26.5	37.1	43.9	50.0	55.7	61.0	65.9		74.8	78.8	82.5	STABLE S.F. = 5/89		
20	25	23.7		STABLE - EXCEEDS 10 x SLOPE HEIGHT											

TABLE 13: BASE CASE 2 - VARIATION OF B

B deg.	Distance of crack from toe - metres Crack No. 1	2	3	4	5	6	7	8	9	10	11	12	13	14
-10	15.0	26.0	36.1	44.9	54.5	65.0	76.3	88.7	102.3	To 17 CRACKS AT 268.3 m, CONTINUES - EXCEEDS 10 x HEIGHT				
-15	17.6	30.1	41.0	49.8	59.2	69.0	79.3	90.2	101.7	To 20 CRACKS AT 279.5 m - EXCEEDS 10 x HEIGHT				
+ 5 (base)	27.5	39.1	26.4	53.1	59.2	64.8	69.9	74.7	79.2	83.2	86.9	STABLE S.F. = 5.61		
+ 10		STABLE S.F. OF REMAINING WEDGE = 1.76												

1. It will be noted in many of the runs reported in this base case sensitivity study that many of the runs were terminated when the distance from the toe of the slope exceeded 10 times the slope height. This limit was introduced into the program to prevent the analysis going on ad infinitum.

This limit can be envoked in both stable and unstable cases. In stable cases, (e.g. Table 8 - variation of H_2), the remaining wedge is stable but when H_2 is large the 10 x slope height limit is triggered before the wedge outcrops at surface. Thus the safety factor of this remaining wedge is not able to be determined.

A second "stable" case can occur (e.g. Table 10, $H_w = 17.8$ m) where no cracks are formed prior to the 10 times slope height limit being envoked. In this case it would seem most likely that the wedge is stable but it is the theoretically conceivable that it might be unstable.

The limit is also triggered in an unstable case where a very large, or an infinite number of cracks occur. Thus the program is stopped running to infinity.

2. The conclusions with respect to H_2 are the same as base case 1.

3. When i_1 and i_2 are varied, as expected, the influence is greater in this case than that of base case 1. Nonetheless the conclusions remain the same.

4. No new conclusions result from the variation of H_w. This still remains the most sensitive and important parameter.

5. Likewise the general conclusions from variations of T, c and ϕ remain unchanged.

6. The variation with β is interesting. The program operates with negative β values (i.e. the failure plane dips away from the slope) and indeed, if

cracking initiates these may be less stable than for positive β values because the water pressures increase with each successive block back into the slope.

As β increases in the positive direction (5° to 10°) so the stability also increases. At first sight this appears to be contrary to standard thinking since initially it would be expected that the steeper failure plane the more likely is the wedge to fail. Indeed this will be the case with high β values. However in this intermediate range the reduction in the water pressure due to rising up the failure plane is greater than the increase in component of weight down the slope; hence stablility increases. This emphasises the sensitivity to the water table height and emphasises the value of using the program to solve the problem; clearly intuition could be lead astray in this case.

2.3 Summary of conclusions and their mining implications

1. For very low angle failure planes (β = low values), the pit slope stability improves as the overburden height increases. This is the only mode of pit slope failure in which this can occur. (This presumes that the water table height above the toe remains constant).

Consequently a mine experiencing this problem may run out of the problem as mining goes to greater depths. However it would seem unlikely that as water table height above the pit toe would in fact remain constant. A more likely case would be that the depth of the water table below surface would remain constant. If this were the case, the uplift force would increase with depth and stability would be reduced with increasing depth of overburden.

2. The pit slope stability is exceptionally sensitive to the water table height, H_w. Small increments in the water table above some critical level can change the slope from stable to unstable with extensive cracking.

Consequently:

(a) It is essential to gather as much data on the water table level as possible, and to monitor this level, if good analyses are to be performed using this program.

(b) Clearly, if drainage of the slope is a practical possibility, then this offers the most reliable method of controlling or preventing slope failures by this mode. The program can be used to evaluate the critical level to which the water table should be lowered to prevent or to limit the extent of failure.

3. The next most important variable is β the angle of the failure plane. When β has low positive or negative values and fracture occurs, this fracturing can extend theoretically an infinite distance back from the toe of the slope. In practice, as will be seen from the case histories, it may extend back at least five times the slope height.

4. The stability of the slope is relatively insensitive to variations in the slope angles i_1 and i_2. Consequently slope flattening is not likely to be a sensible control method.

5. The variables T, c and ϕ are clearly important but the overiding effect of the water table height reduces these variables to a second order of importance.

6. The number of crack sets that may occur can vary widely and is sensitive to many of the variables. Thus the fact that 1 or 10 or 20 crack sets occur is not important with respect to stability (and indeed could vary with minor variations of the geotechnical parameters). What is of much greater importance is the total extent of cracking i.e. the distance of the last crack from the toe. This can be used as a relative measure of stability.

3. Case histories

Initially it was planned to document the case histories of this mode of failure from field observations. This was done for the Highvale (1984) study (case history #4). However, the other mine where this type of failure had occurred in past years, did not experience a failure during the study period and consequently no documentation was possible. With the permission of the scientific authority for this contract, the second field study was therefore replaced with three case histories reported in the literature. With each of these studies reported in the literature the mode of retrogressive failure of the pit slope postulated and reported is different from that of multiple block plane shear slope failure. Nevertheless it is shown in all three cases that MBPSSF could provide an alternative explanation of the failure mechanisms. However, it is not possible at this time to differentiate which explanation is the correct one, since sufficient information is not available. These case histories will now be considered in turn, in detail.

3.1 Case History #1: Landslides at Folkestone Warren

In 1969 Hutchinson (1) published a paper entitled "A Reconsideration of the Coastal Landslides at Folkestone Warren, Kent." The initiation of these landslides probably took place between 300 and 500 B.C. All the deep seated landslides in the Warren recorded during the past two centuries are shown by Hutchinson to have occurred in the period of seasonally high ground water levels in the slipped masses, from December to March. The paper concentrates on the analysis of the deep seated renewals of movement on non-circular slip surfaces which occurred in 1915, 1937 and 1940. In addition, Hutchinson proposes a mechanism for retrogression of the rear scarps of the landslides as a possible explanation of the original initiation of these slides.

It is this latter mechanism which is of interest in this case study and no further attention will be given to the later renewed movements which form the bulk of work presented in this paper, other than the general geological description and material properties derived from this work. It will be shown that "multiple block plane shear failure" could offer an alternative explanation of this regression mechanism.

General Description and Geological setting

Folkestone Warren comprises the extensive area of coastal landslides, involving the Chalk and the Gault, between Folkestone and Dover in south-east Kent, England. The most striking topographic features are shown in Figure 2. Figure 3 shows a simplified cross section; it should be noted from this figure that it is not the "type R" and "type M" landslips shown that are of concern in this case history but rather the retrogressive mechanism in the high chalk cliffs.

Folkestone Beds

At Folkestone, this formation is about 60 ft. thick and consists of coarse yellowish green-sands with bands of calcareous and glauconitic sandstone. The junction between the Folkestone beds and the overlying Gault is taken at the top of the "Sulphur band", a bed of phosphate nodules in the Folkestone East Cliff section. The Folkestone beds are generally described as being "highly permeable".

Gault

The Gault consists predominantly of hard, over consolidated, fissured and jointed clays. It is generally taken to extend from the top of the Sulphur band up to the base of the Chloritic Marl. The formation is divided into the dark grey layers of the lower Gault and the pale grey, marly clays of the upper Gault. At Folkestone the Upper Gault constitutes nearly three quarters of the total thickness of the formation

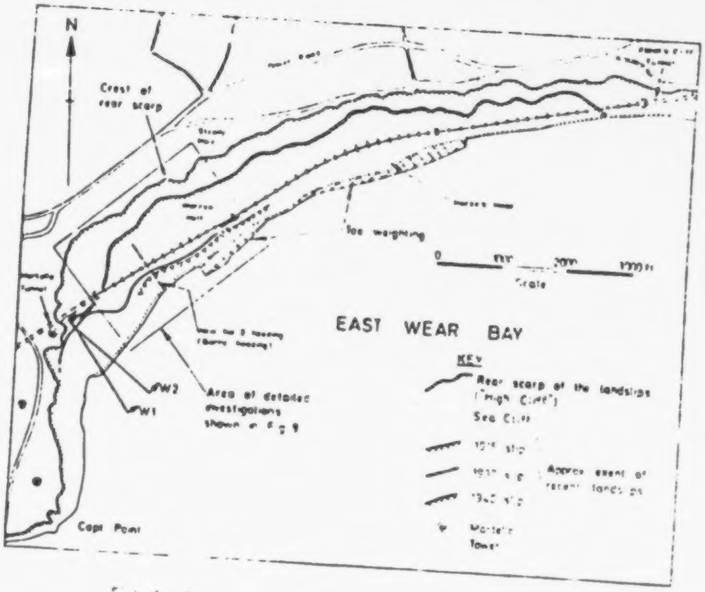

N
Crest of rear scarp
W2
W1
Area of detailed investigations shown in Fig 9
Toe weighting
0
Scale
EAST WEAR BAY
KEY
Rear scarp of the landslips ("High Cliff")
Sea Cliff
Approx extent of recent landslips
Martello Tower
Copt Point

FIG 2 General site plan

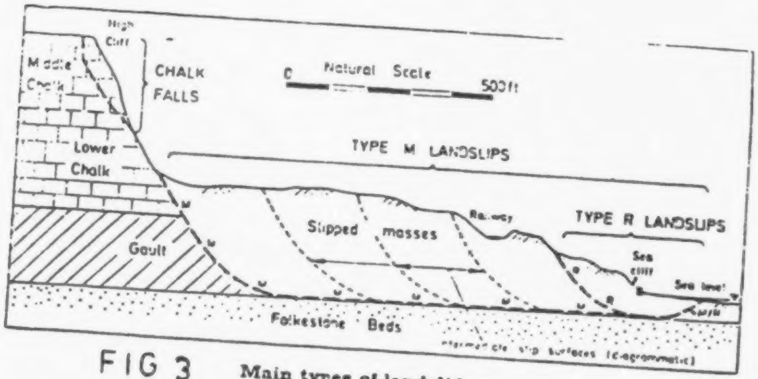

High Cliff
Middle Chalk
CHALK FALLS
0 Natural Scale 500ft
Lower Chalk
TYPE M LANDSLIPS
Gault
Slipped masses
Railway
TYPE R LANDSLIPS
Sea cliff
Sea level
Folkestone Beds
Intermediate slip surfaces (diagrammatic)

FIG 3 Main types of landslide occurring

The total thickness of the undisturbed Gault behind Folkestone Warren is between about 140 and 160 ft.

Chalk

The lowest bed of the Lower Chalk is a glauconitic, sandy marl about 10 ft. thick; this is overlain by the Chalk Marl, a relatively intact and and impervious formation about 90 ft. thick. The overlying grey chalk, about 80 ft. thick, is formed of material transitional between chalk marl and the white chalk and is massive and blocky in its upper parts. The lower chalk is completed by about 60 ft. of massive, much jointed, white chalk and the overlying 6 ft. layer of marls. The superincumbent middle chalk has at its base a bed of nodular, gritty, yellowish white chalk approximately 40 ft thick. This passes upwards into form white chalk in massive, well jointed and highly pervious beds.

Ground water conditons

In this case history only the ground water conditions in the high cliffs will be considered. The ground water conditions reported for the slipped masses and for the underlying Folkestone beds are not relevant to the case study for the retrogressive failures in the high cliffs.

The ground water in the chalk is tapped by numerous wells of which the nearest to Folkestone Warren were at Hope Farm, 2/3 mile N.W. of High Cliff, and Coombe Farm a further 1½ miles inland (Figure 4).

The water levels were gauged between 1899 and 1906 by Stilgoe (2). At the Coombe Farm well they were observed to vary seasonally between about +222 and +273 ft. O.D. The levels at Hope Farm varied only between about +262 and +278 ft. O.D. in the same period. The relationship between the water levels at these two wells and those known to exist in the slipped masses of the Warren is shown in Figure 5.

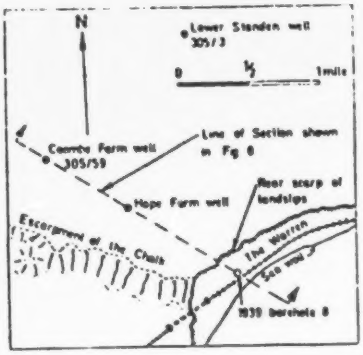

N
Lower Standen well
305/3
0
½
1mile
Coombe Farm well
305/59
Line of Section shown in Fig 8
Hope Farm well
Rear scarp of landslips
Escarpment of the Chalk
The Warren
Sea wall
1939 borehole 8

FIG 4 Location of wells in the Chalk inland

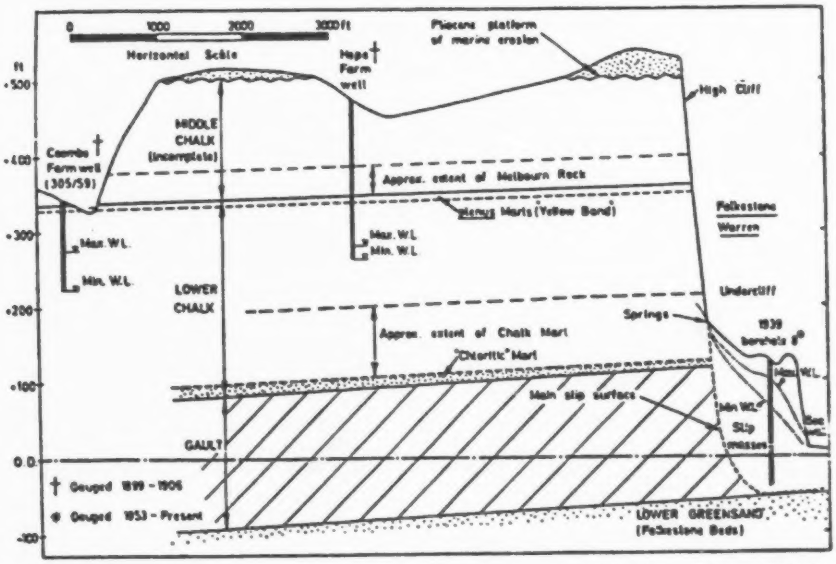

0
1000
2000
3000 ft
Horizontal Scale
ft
+500
+400
+300
+200
+100
0.D.
-100
Hope Farm well †
Pliocene platform of marine erosion
High Cliff
Coombe Farm well † (305/59)
MIDDLE CHALK (incomplete)
Approx. extent of Melbourn Rock
Plenus Marls (Yellow Band)
Folkestone Warren
Max. W.L.
Min. W.L.
Max. W.L.
Min. W.L.
LOWER CHALK
Undercliff
Springs
1939 borehole 8
Approx. extent of Chalk Marl
"Chloritic" Marl
Max. W.L.
Main slip surface
Min. W.L.
Slip masses
Sea wall
GAULT
† Gauged 1899 - 1906
● Gauged 1953 - Present
LOWER GREENSAND (Folkestone Beds)

FIG 5 Ground-water conditions in the slipped masses and in the adjacent Chalk

For the purposes of the "multiple block plane shear analysis" to be carried out later, it will be assumed that

(i) the water table is horizontal (clearly from Figure 5 this is not the case since the position of the springs in High Cliff indicate a draw down).

(ii) the water levels are those observed at Coombe farm; i.e. a maximum of 273 ft. O.D. and a minimum of 222 ft. O.D.

Laboratory Shear Strength Tests

A limited number of laboratory shear strength tests have been carried out, primarily to explore the peak and residual strength of the Gault.

A large variation of liquid limit throughout the thickness of the Gault indicates that widely different shear strengths are likely to obtain in the various horizons of the formation. Fortunately the high liquid limit zone near the base of the Gault was well exposed. Block sample 2, having the highest liquid limit, was chosen for strength testing. Shear tests were carried out in 6 cm x 6 cm shear boxes; after the undisturbed specimens had been consolidated for two days they were sheared paralled to the bedding at a rate of 5.4×10^{-5} in/min to determine their peak strength. Subsequently a smooth plane was cut through each specimen, after further consolidation for one day the cut specimens were sheared at a rate of 1.2×10^{-4} in/min to determine their residual strength. Figure 6 shows typical stress displacement curves for these peak and residual tests. Figure 7 shows the peak and residual strength envelopes for a range of effective normal pressures up to 54 lbs/sq. in. The corresponding shear strength parameters for sample 2 of the Gault are:

Peak : $c^{1} = 18$ lbs/sq. in. (2592 p.s.f.), $\phi^{1} = 33^{\circ}$

Residual: $c_r^{1} = 0$ lbs/sq. in., $\phi_r^{1} = 12^{\circ}$

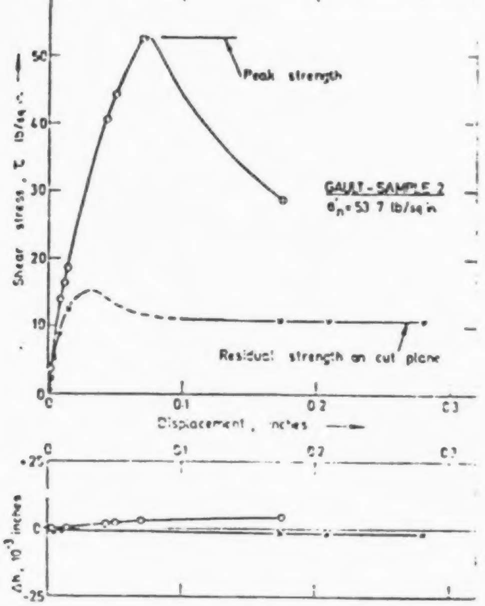


FIG 6 Typical stress-displacement curves for Gault, sample 2

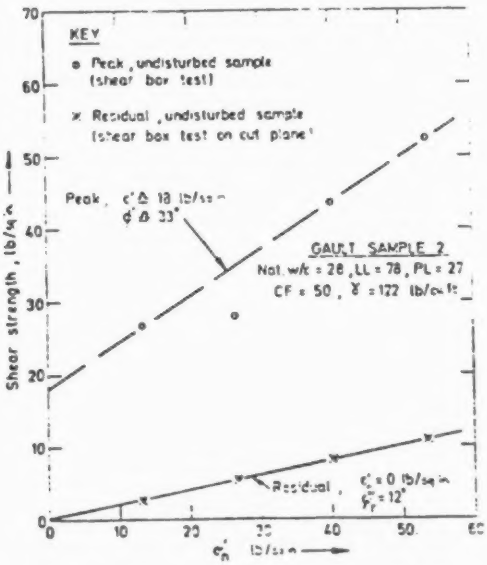


FIG 7 Results of drained shear tests on Gault, sample 2

These peak values will be values used in the multiple block plane shear failure analysis.

Retrogressive mechanism suggested by Hutchinson

At Folkestone Warren the over consolidated Gault lies between two more rigid strata, the Folkestone beds below and the Chalk above. Under such conditions Hutchinson suggested that retrogression of the rear scarp will occur by the mechanism outlined in Figure 8, stages I to III. It is suggested that the lateral expansion of the seaward parts of the Gault, resulting from the reduction of their side support by marine erosion and land slipping, will have been accompanied by the generation landwards of a shear surface of residual strength situated at or near the base of the Gault (Figure 8, stage I). A possible method for progressive failure involved in the generation of such a shear surface has been given by Bjerrum (3). A further result of such a seawards expansion of the Gault is that the chalk cap rock will have been thrown into tension with the consequent opening of its coastwise vertical joints. It seems likely that features known as "vents" (Figure 8, stage I) were initiated in this way.

Consider now the stability of block ABCDE. The forces resisting its collapse will have been greatly diminished by the movements outlined, partly by the reduction of the strength on the basal surface CD to its residual value and partly by the opening of the previously interlocked joint AB. A greatly increased load will thus have been thrown onto the remaining part of the eventual failure path BC. If insufficient support is provided by the slipped masses to seaward, the blockwill fail and begin to slide.

As stage II illustrates, however, with increasing subsidence the curvature of the surface B.C. produces a back tilt of the failing block which will bring about a re-engagement of a part of the irregular joint face as AB. Although the whole failure surface BCD will now be at its residual strength, the stabilizing contribution of the re-engaged joint may be sufficient to

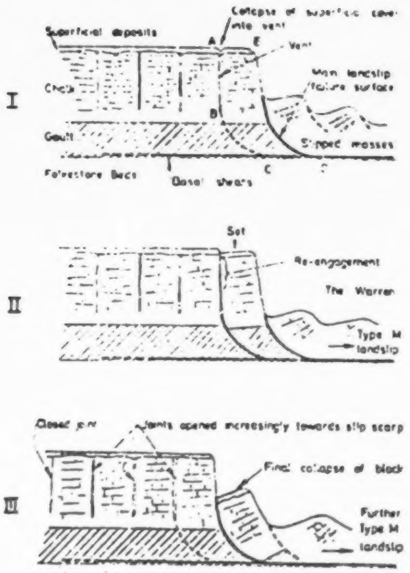

Collapse of superficial cover into vent
Superficial deposits
A
E
Vent
Main landslip failure surface
I
Chalk
B
Gault
Slipped masses
Folkestone Beds
Basal shears
C
D
Set
Re-engagement
The Warren
II
Type M landslip
Closed joint
Joints opened increasingly towards slip scarp
Final collapse of block
III
Further Type M landslip

FIG2 : Suggested mechanism of retrogression

effect a temporary cessation of movement. Final collapse of the block (Stage III) will generally coincide with the next reduction of support by the slipped masses. The cycle of retrogession may then be repeated on the next block to landward.

Some evidence of the existence of a plane of basal shear is provided by three boreholes drilled in 1948-50. Near horizontal slickensides, described as "basal slips", were reported at -42.5 and -40.5 ft. OD (1 to 3 ft above the base of the Gault) by Toms (4). A "plastic zone" in the Gault at the corresponding horizon in an adjoining borehole was noted by Wood (5). A further horizontal slickensided surface was logged at -19.5 ft. OD (10 ft. above the base of the Gault) in another borehole by Toms (4).

Comparison of Hutchinson's retrogressive mechanism with multiple block plane shear failure

There are many close similarities between the mechanism suggested above by Hutchinson and the multiple block plane shear failure proposed by the authors. It is therefore probably of greater interest to highlight the differences:-

(i) The existence of large horizontal stresses in over consolidated plastic clays is well attested, as is the lateral expansion of such deposits upon reduction of their lateral support. Such expansion clearly is compatible and will contribute to a mechanism of multiple block plane shear failure but is not a critical requirement for such failure, whereas it is an essential requirement for the mechanism suggested by Hutchinson.

(ii) The effect of pore water pressures at the failure level has not been mentioned by Hutchinson although clearly they must play a major part in the failure mechanism. Water pressures are the prime mode of failure initiation in multiple block plane shear failure and explain why lateral stress relief is not critical to the multiple block plane shear failure mode.

(iii) Hutchinson (and Bjerrum) postulate that the lateral expansion generates a basal slip plane of residual strength in stage I. Multiple block plane shear failure requires the overcoming of the peak shear strength on the potential slip plane.

(iv) The remaining difference of whether there is a very steep shear failure surface (Hutchinson) or a vertical tension crack is probably of little practical importance.

The past failure mechanisms of sliding and collapse of the failed block, re-engagement of joints with possible temporary stability and final stabilization by the loading from the slipped masses are totally compatible. However, Hutchinson does ignore the likely drop in water pressure that will accompany stage I failure which would also contribute significantly to re-stabilising of the rock mass in addition to re-engagement of joints.

It will therefore be of great interest to carry out a multiple block plane shear failure analysis using the data given in this paper to examine whether or not multiple block plane shear failure could also explain these retrogressive failures in the high cliffs. This will now be done.

Multiple block plane shear failure analysis

Figures (9) and (10) show the cross section given in Hutchinson's paper and the geometry considered in the following multiple block plane shear analysis. It is assumed in this analysis that the shear plane occurs at a horizon just above the Gault/Folkestone contact at a level of -80 ft. O.D. The total slope height is thus approximately 580 ft.; the slope angle is assumed to be 70°. The tensile strength of the rock is taken as 0 p.s.f. due to the frequent jointing. The cohesion and angle of friction of the Gault are

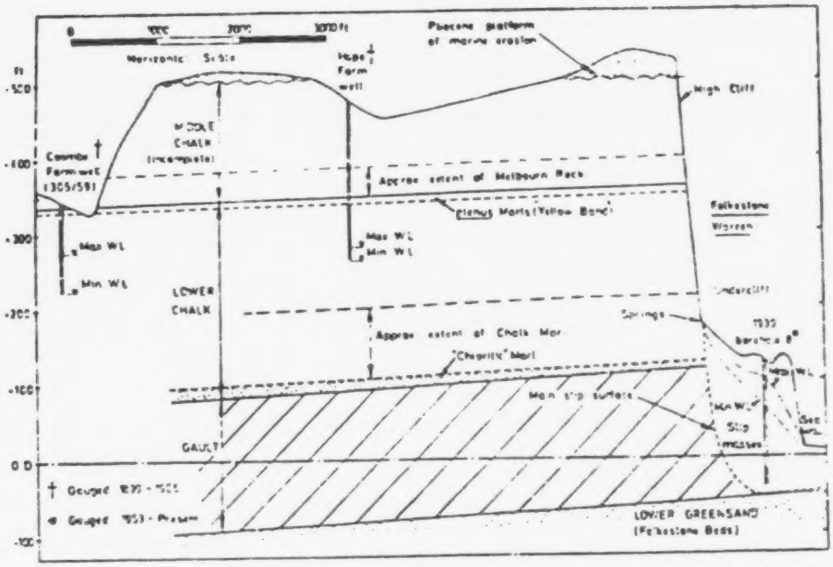

0
1000
2000
3000 ft
Horizontal Scale
Hope Farm well
Pliocene platform of marine erosion
ft
+500
+400
+300
+200
+100
0 D
-100
Coombe Farm well (305/59)
MIDDLE CHALK (incomplete)
High Cliff
Approx extent of Melbourn Rock
Plenus Marls (Yellow Band)
Folkestone Warren
Max WL
Min WL
LOWER CHALK
Undercliff
Springs
1939 borehole 8
Approx extent of Chalk Marl
"Chloritic" Marl
Max WL
Main slip surface
Min WL
Slip masses
GAULT
Sea
Gauged 1939 - 1955
Gauged 1953 - Present
LOWER GREENSAND (Folkestone Beds)

FIG 9 **Ground-water conditions in the slipped masses and in the adjacent Chalk**

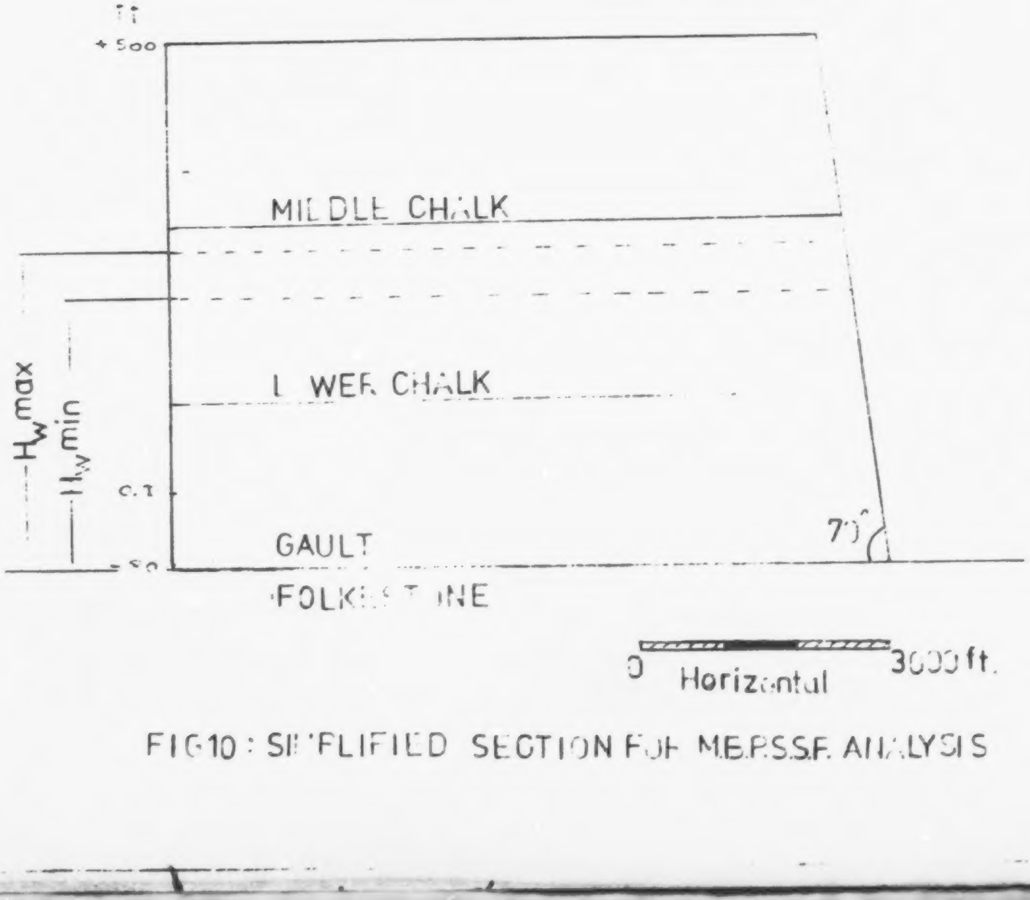

ft
+500
MIDDLE CHALK
LOWER CHALK
$H_w$max
$H_w$min
0.D
-50
GAULT
FOLKESTONE
70°
0
Horizontal
3000 ft.

FIG 10 : SIMPLIFIED SECTION FOR M.E.R.S.S.F. ANALYSIS

taken as 2592 p.s.f. and 33° respectively. It is assumed that the failure plane is horizontal ($\beta = 0^o$).

Two deterministic solutions were run; the first for the minimum water level of +222ft. OD (i.e. $H_w \sim 300$ ft) and the second for the maximum recorded piezometric level of +273 H OD (i.e. $H_w \sim 350$ ft). Tables 14 and 15 list the input values and the results for the first few cracks. Table 16 summarises the upper and lower bound solutions for each case.

Discussion

From the multiple block plane shear slope failure (MBPSSF) analysis at the lower water level only one crack occurs; this being in the cliff face. At the maximum water table level an infinite number of cracks occur; they repeat every 68.3 ft. back into the crest of the cliff.

It is thus clear that regressive failure back into the cliff crest can occur at some critical water table level between the maximum and minimum recorded values. Consequently multiple block plane shear slope failure could account for the retrogressive failures occuring in the High Cliff at Folkestone Warren.

This is not to say that the mechanism proposed by Hutchinson is invalid but merely that an alternative explanation is also possible. It is not possible, from the data presented, to establish which mechanism is correct.

In the authors' opinion, Hutchinson pays far too little attention to the influence of the water table on this mode of failure. In addition, whilst he gives a logical mechanism of failure, he does not present an analysis technique for his mode of failure. In particular, the requirement by Hutchinson that the shear plane must reach residual strength is disturbing and it is shown that this assumption is unnecessary with multiple block plane shear failure. Peak strengths can be used in MBPSSF failure analysis with equally satisfactory results provided that due account is taken of the water table level.

TABLE 14

```
                    ****************************************************
                    *                                                  *
                    *                      MBPSSF                      *
                    *     Multiple Block Plane Shear Slope Failure     *
                    *                                                  *
                    ****************************************************


Test Case #3   Folkestone


Geometric Data                                                                 (H1)    =      0 0  ft
                 Height of the upper slope                                     (H2)    =    580 00 ft
                 Height of the lower slope                                     (Hw)    =    300 00 ft
                 Height of the water table                                     (Xb)    =      0 0  ft
                 Bench width                                                   (Ai1)   =     70 00 deg
                 Angle of the upper slope with the horizontal                  (Ai2)   =     70 00 deg
                 Angle of the lower slope with the horizontal                  (Beta)  =      0 00 deg
                 Angle of the failure plane with the horizontal               (Delta)       0 1000 ft
                 Incremental horizontal distance


Material Properties                                                            (T)     =      0 0   psf
                 Tensile strength of the rock                                  (C)     =   2592 000 psf
                 Effective cohesion on the failure surface                   (Gamma)   =    162 000 pcf
                 Density of rock in the failed wedge                        (Gammaw)   =     62 400 pcf
                 Density of water                                              (Phi)         33 000 deg
                 Effective angle of friction on the failure plane

********************************************************************************
Run #  1      Type of Analysis  Deterministic (option 2)
********************************************************************************


  Solution number   1    Crack number   1        (Lower limit)                                              (SF)         0 9911
    Factor of Safety                                                                                        (W)    =5600912 61 lbs
    Weight of failed wedge between cracks  0 and  1                                                         (At)   =     158 70 sq ft
    Total area of the failure plane, of unit depth, between cracks  0 and  1                                (U)    =1948088 31 lbs
    Total uplift force due to water pressure acting on the failure plane between cracks  0 and  1           (V)    =2807948 16 lbs
    Force applied to the failed wedge by the water in crack  1                                              (T)    =       0 0  lbs
    Resisting force due to tensile strength across the potential crack  1                                 (Kn+1)   =     158 70 ft
    Horizontal distance between cracks  0 and  1                                                          (Zn+1)   =     580 00 ft
    Depth of crack  1 below surface                                                              (SUMKN + Kn+1)   =     158 70 ft
    Distance to crack from toe of slope

    Case A4(a)    HW > B ie  300 00 >    0 00

  Solution number   1    Crack number   1        (Upper limit)                                              (SF)   =     1 0092
    Factor of Safety                                                                                        (W)    =5700165 32 lbs
    Weight of failed wedge between cracks  0 and  1                                                         (At)   =     160 10 sq ft
    Total area of the failure plane, of unit depth, between cracks  0 and  1                                (U)    =1974296 07 lbs
    Total uplift force due to water pressure acting on the failure plane between cracks  0 and  1           (V)    =2807947 70 lbs
    Total uplift force due to water pressure acting on the failure plane between cracks  0 and  1           (T)    =       0 0  lbs
    Force applied to the failed wedge by the water in crack  1                                            (Kn+1)   =     160 10 ft
    Resisting force due to tensile strength across the potential crack  1                                 (Zn+1)   =     580 00 ft
    Horizontal distance between cracks  0 and  1                                                 (SUMKN + Kn+1)   =     160 10 ft
    Depth of crack  1 below surface
    Distance to crack from toe of slope


  Program Run Terminated
  Distance from toe of slope to last crack exceeds 10 x total slope height

  Completion of run #  1 (Total of  1 runs were requested)

  Finish
```

TABLE 15

```
          ************************************************
          *                                              *
          *                    MBPSSF                    *
          *   Multiple Block Plane Shear Slope Failure   *
          *                                              *
          ************************************************


Test Case #3 - Folkestone


Geometric Data                                                        (H1)   =      0.0  ft
             Height of the upper slope                                (H2)   =    580.00 ft
             Height of the lower slope                                (Hw)   =    350.00 ft
             Height of the wate  table                                (Xb)   =      0.0  ft
             Bench width                                              (A11)  =     70.00 deg
             Angle of the upper slope with the horizontal             (A12)  =     70.00 deg
             Angle of the lower slope with the horizontal             (Beta) =      0.00 deg
             Angle of the failure plane with the horizontal          (Delta) =     0.1000 ft
             Incremental horizontal distance


Material Properties                                                   (T)    =      0.0   psf
             Tensile strength of the rock                             (C)    =   2592.000 psf
             Effective cohesion on the failure surface             (Gamma)   =    162.000 pcf
             Density of rock in the failed wedge                  (Gammaw)   =     62.400 pcf
             Density of water                                        (Phi)   =     33.000 deg
             Effective angle of friction on the failure plane


*******************************************************************************
Run #  1     Type of Analysis  Deterministic (option 2)
*******************************************************************************


Solution number  1    Crack number  1         (Lower limit)                                                   (SF)   =      0.9905
  Factor of Safety                                                                                            (W)    =7726569.48 lbs
  Weight of failed wedge between cracks  0 and  1                                                             (At)   =    187.00 sq ft
  Total area of the failure plane, of unit depth, between cracks  0 and  1                                    (U)    =2691968.27 lbs
  Total uplift force due to water pressure acting on the failure plane between cracks  0 and  1               (V)    =3821928.73 lbs
  Force applied to the failed wedge by the water in crack  1                                                  (Y)    =      0.0  lbs
  Resisting force due to tensile strength across the potential crack  1                                   (Kn+1)    =    187.00 ft
  Horizontal distance between cracks  0 and  1                                                            (Zn+1)    =    580.00 ft
  Depth of crack  1 below surface                                                                (SUMKN + Kn+1)    =    187.00 ft
  Distance to crack from toe of slope

  Case A4(a) - Hw > B le  350.00 >     0.00


Solution number  1    Crack number  1         (Upper limit)                                                   (SF)   =      1.0095
  Factor of Safety                                                                                            (W)    =7918603.33 lbs
  Weight of failed wedge between cracks  0 and  1                                                             (At)   =    188.70 sq ft
  Total area of the failure plane, of unit depth, between cracks  0 and  1                                    (U)    =2729095.92 lbs
  Total uplift force due to water pressure acting on the failure plane between cracks  0 and  1               (V)    =3821928.09 lbs
  Force applied to the failed wedge by the water in crack  1..                                                (Y)    =      0.0  lbs
  Resisting force due to tensile strength across the potential crack  1                                   (Kn+1)    =    188.70 ft
  Horizontal distance between cracks  0 and  1 ...                                                        (Zn+1)    =    580.00 ft
  Depth of crack  1 below surface                                                                (SUMKN + Kn+1)    =    188.70 ft

  Distance to crack from toe of slope


Solution number  1    Crack number  2         (Lower limit)                                                   (SF)   =      0.9306
  Factor of Safety .......                                                                                   .(W)    =6279465.85 lbs
  Weight of failed wedge between cracks  1 and  2. .................                                          (At)   =     69.10 sq ft
  Total area of the failure plane, of unit depth, between cracks  1 and  2.                                   (U)    = 833529.63 lbs
  Total uplift force due to water pressure acting on the failure plane between cracks  1 and  2 .             (V)    =3821901.75 lbs
  Total uplift force due to water in crack  2.......                                                          (Y)    =      0.0  lbs
  Force applied to the failed wedge by the water in crack  2....                                         .(Kn+1)    =     69.10 ft
  Resisting force due to tensile strength across the potential crack  2....                              .(Zn+1)    =    580.00 ft
  Horizontal distance between cracks  1 and  2.......  ....                                       (SUMKN + Kn+1)    =    257.80 ft
  Depth of crack  2 below surface
  Distance to crack from toe of slope

  Case A1(a) - Hw > B le  350.00 >     0.00


Solution number  1    Crack number  2         (Upper limit)                                                  .(SF)   =      1.0087
  Factor of Safety .......                                                                                   .(W)    =6511008.83 lbs
  Weight of failed wedge between cracks  1 and  2.......                                                     .(At)   =     70.50 sq ft
  Total area of the failure plane, of unit depth, between cracks  1 and  2.                                 ..(U)    = 854105.23 lbs
  Total uplift force due to water pressure acting on the failure plane between cracks  1 and  2..             (V)    =3821901.22 lbs
  Total uplift force due to water in crack  2..                                                               (Y)    =      0.0  lbs
  Force applied to the failed wedge by the water in crack  2.                                             (Kn+1)    =     70.50 ft
  Resisting force due to tensile strength across the potential crack  2                                   (Zn+1)    =    580.00 ft
  Horizontal distance between cracks  1 and  2                                                   (SUMKN + Kn+1)    =    259.20 ft
  Depth of crack  2 below surface
  Distance to crack from toe of slope


Solution number  1    Crack number  3         (Lower limit)                                                   (SF)   =      0.9905
  Factor of Safety ....                                                                                       (W)    =6295264.56 lbs
  Weight of failed wedge between cracks  2 and  3.........                                                 ..(At)   =     67.00 sq ft
  Total area of the failure plane, of unit depth, between cracks  2 and  3                                    (U)    = 731628.10 lbs
  Total uplift force due to water pressure acting on the failure plane between cracks  2 and  3              .(V)    =3821875.68 lbs
  Total uplift force due to water in crack  3.                                                             ...(Y)    =      0.0  lbs
  Force applied to the failed wedge by the water in crack  3                                             .(Kn+1)    =     67.00 ft
  Resisting force due to tensile strength across the potential crack  3                                  .(Zn+1)    =    579.99 ft
  Horizontal distance between cracks  2 and  3..                                                 (SUMKN + Kn+1)    =    326.20 ft
  Depth of crack  3 below surface.....
  Distance to crack from toe of slope

  Case D1(a) - Hw > B le  350.00 >     0.01


Solution number  1    Crack number  3         (Upper limit)                                                   (SF)   =      1.0098
  Factor of Safety...............                                                                             (W)    =6417411.36 lbs
  Weight of failed wedge between cracks  2 and  3.............                                                (At)   =     68.30 sq ft
  Total area of the failure plane, of unit depth, between cracks  2 and  3                                 ...(U)    = 745823.82 lbs
  Total uplift force due to water pressure acting on the failure plane between cracks  2 and  3.              (V)    =3821875.19 lbs
  Total uplift force due to water in crack  3.......                                                       ...(Y)    =      0.0  lbs
  Force applied to the failed wedge by the water in crack  3                                            ..(Kn+1)    =     68.30 ft
  Resisting force due to tensile strength across the potential crack  3                                  .(Zn+1)    =    579.99 ft
  Horizontal distance between cracks  2 and  3..........                                         (SUMKN + Kn+1)    =    327.90 ft
  Depth of crack  3 below surface....
  Distance to crack from toe of slope
```

TABLE 16

Test Case #3 - Folkestone

CASE 1: Hw = 300 ft.

Summary (lower limit)
Distance to crack number

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Run 1	158.7													

Summary (upper limit)
Distance to crack number

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Run 1	160.1													

CASE 2: Hw = 350 Ft.

Summary (lower limit)
Distance to crack number

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Run 1	187	257.8	326.2	394.5	462.8	531.1	599.4	667.7	736	804.3	872.6	940.9	1009.2	1077.5

Summary (upper Limit)
Distance to crack number

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Run 1	187.7	259.2	327.5	395.8	464.1	532.4	600.7	669	737.3	805.6	873.9	942.2	1010.5	1078.8

In this latter case (Hw = 350 ft.) there will be an infinite number of cracks each an additional 68.3 ft. beyond the preceeding set.

3.2 Case History #2: Progressive Failure caused by a Deep Excavation in Oxford Clay.

In 1977, Burland et al (6) published a paper entitled "A study of ground movement and progressive failure caused by a deep excavation in Oxford clay". This presents a study of a 29m deep brickpit which was progressively excavated in overconsolidated Oxford clay and showed that the surrounding ground within a distance of 60m was affected by movement. Once again, these authors use the mechanism of progressive failure discussed by Bjerrum (3) to explain the retrogressive failure mechanisms. It will be shown here that MBPSSF failure could also offer an alternative explanation for this failure.

General description and geological setting

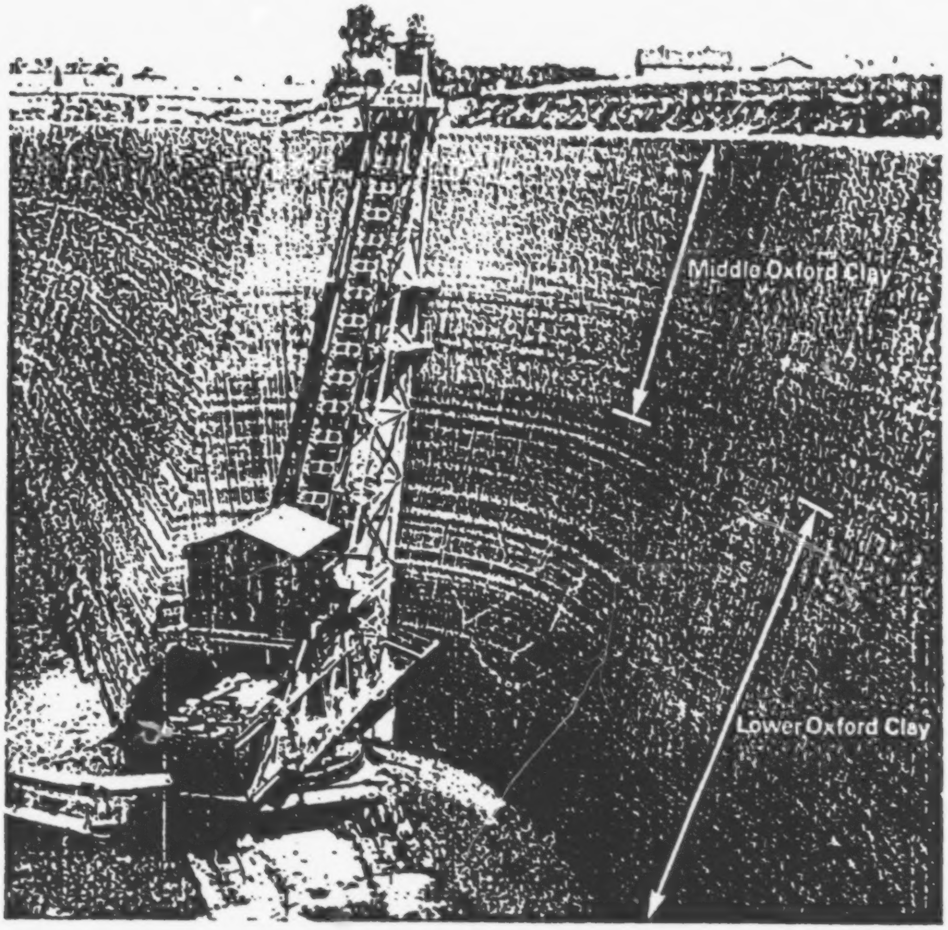
The Saxon pit lies just to the west of Whittlesey on the southern margin of an island of Oxford Clay. The present pit had been in use for 10 years prior to the investigation and, by 1969, the 200 m working face had advanced approximately 65m . The base of the pit is well below natural ground water level and continuous drainage is necessary.

Before excavation of the Oxford Clay, a 3-5m mantle of sands, gravels and weathered clay is periodically stripped. The Oxford clay is then cut in a 25m high face sloping at 72° by the planer shown in Figure 11.

During the study period six complete traverses of the face were made, leaving the faces donated A to G on Figures 12 and 13.

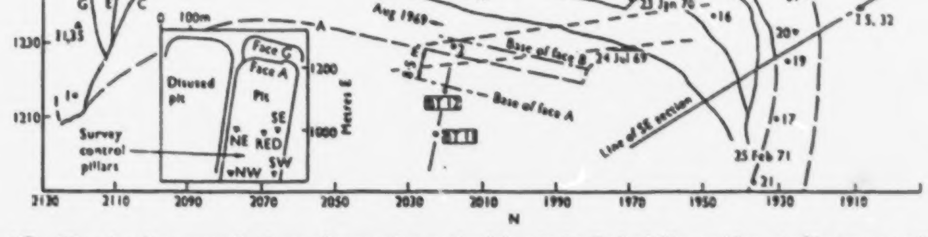
The site is overlain by 3 - 6 m of callow, recent deposits, consisting mostly of peat, sandy gravel and completely weathered Oxford clay. Beneath this, the Oxford Clay comprises 8 - 10 m of the Middle Oxford Clay overlying 17 m of Lower Oxford clay.

The middle Oxford clay consists, at the top, of moderately weathered clay with frequent brown stained fissures, this clay having a homogeneous



Middle Oxford Clay
Lower Oxford Clay

FIG 11 Planer cutting northwards along the east face of Saxon pit: the major joints can be seen intersecting the slightly darker Lower Oxford Clay in the foreground



Key
Inclinometer
Magnet extensometer
Piezometer
Surface movement points
Major vertical joint
Photogrammetric survey
Tacheometric survey
Scale of metres
0
10
Mar 1971
Oct 1970
May 1970
10 Feb 1970
Dec 1969
Aug 1969
6 Jan 71
16 Mar 70
29 Oct 69
23 Jan 70
24 Jul 69
11 May 71
25 Feb 71
A
B
C
D
E
F
G
Base of face B
Base of face A
Line of SE section
Disused pit
Pit
Face G
Face A
Survey control pillars
NE
RED
SE
SW
NW
0
100m
1200
1000
Metres E
E
N
1310
1290
1270
1250
1230
1210
2130
2110
2090
2070
2050
2030
2010
1990
1970
1950
1930
1910

FIG 12 Plan showing successive faces of excavation, major joints in the Oxford Clay and layout of instrumentation

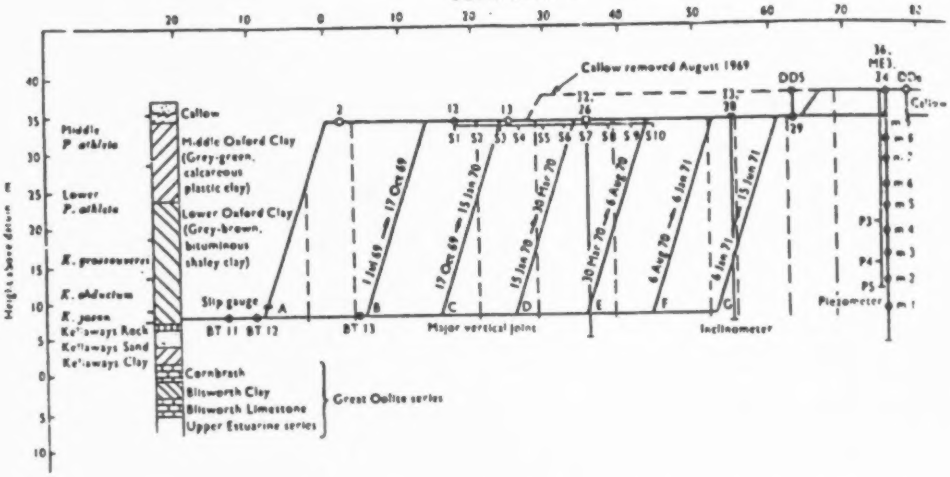

Distance from face m
20
10
0
10
20
30
40
50
60
70
80
Height above datum m
40
35
30
25
20
15
10
5
0
5
10
Middle
P. athleta
Lower
P. athleta
K. grossouvrei
K. obductum
K. jason
Kellaways Rock
Kellaways Sand
Kellaways Clay
Callow
Middle Oxford Clay
(Grey-green,
calcareous
plastic clay)
Lower Oxford Clay
(Grey-brown,
bituminous
shaley clay)
Cornbrash
Blisworth Clay
Blisworth Limestone
Upper Estuarine series
Great Oolite series
Callow removed August 1969
2
12
13
32,
26
33,
28
29
DDS
36,
ME3,
34
DD6
Callow
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
1 Jul 69 — 17 Oct 69
17 Oct 69 — 15 Jan 70
15 Jan 70 — 30 Mar 70
30 Mar 70 — 6 Aug 70
6 Aug 70 — 6 Jan 71
6 Jan 71
15 Jan 71
Slip gauge
A
B
C
D
E
F
G
BT 11
BT 12
BT 13
Major vertical joint
Inclinometer
Piezometer
P3
P4
P5
m 1
m 2
m 3
m 4
m 5
m 6
m 7
m 8
m 9

FIG 13 **Centre line section normal to the face showing position of successive faces and major joints, geology and instrumentation**

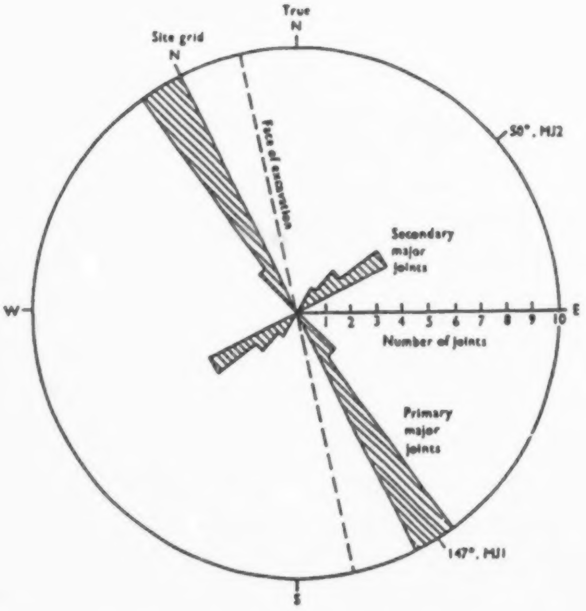


FIG 14 **Orientation and frequency of major joints at Saxon pit**

plastic appearance in the face. The lower part is, however, much less fissured and weathered, the beds having a more blocky appearance. The lower Oxford clay consists of beds of two lithological types. Dark brown-grey, highly bituminous, strongly laminated shales predominate, especially near the base of the face, while interbedded are beds of paler green-grey more blocky clay.

Local Structure

The most obvious structural features at the Saxon pit are near vertical major joints, often extending laterally for hundreds of metres. Two orthogonal sets (Figure 14) of joints are present, each consisting of a near parallel array with a separation of 5 - 20m, as shown by the broken lines in Figures 12 and 13. Joints in one set are approximately normal to the face and tend to remain closed. In contrast, joints in the orthogonal set intersect the face at lower angles and are preferentially opened by stress release, thus appearing more prominent.

Geotechnical Properties

A large number of tests were carried out to determine the geotechnical properties of the strata. Figure 15 summarises these results and Figure 16 shows typical stress-displacement curves and the strength envelope for direct drained shear tests on Lower Oxford Clay specimens.

Shear box tests on intact specimens of Lower Oxford Clay from near the base of the face, sheared parallel to bedding, gave peak parameters of $\phi^1 = 27.5^o$ and $c^1 = 172$ kN/m^2 and residual shear parameters of $\phi_r^1 = 13^o$ and $c_r^1 = 3.5$ kN/m^3.

In the ensuing MBPSSF analysis peak stength parameters of:

$\phi^1 = 28^o$
and $c^1 = 172$ kN/m^2

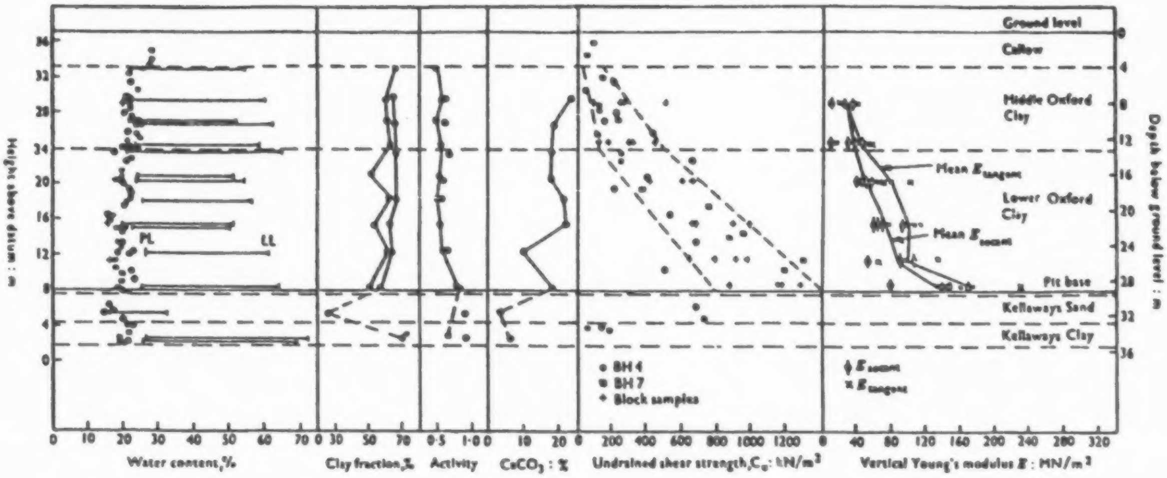


FIG 15 Variation with depth of the geotechnical properties of the Oxford Clay and Kellaways Beds

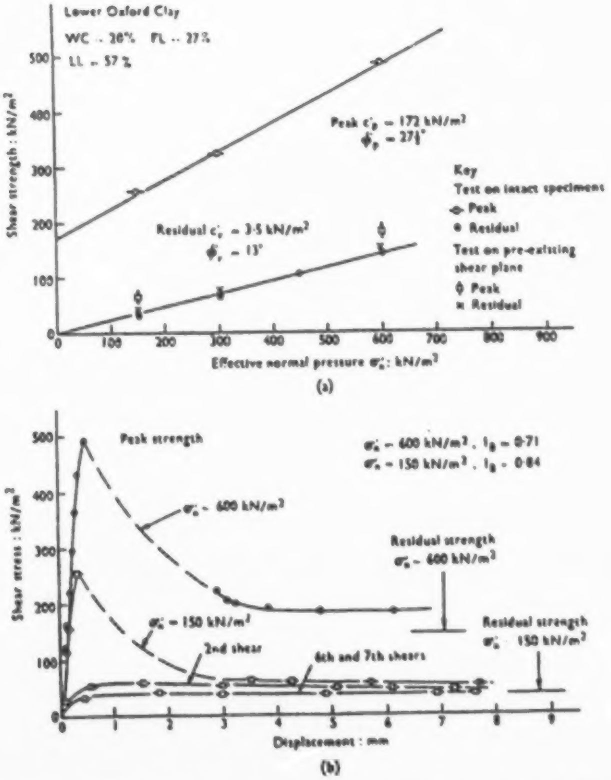


FIG 16 Typical shear stress-displacement curves and strength envelope for direct drained shear tests on Lower Oxford Clay specimens sheared parallel to the bedding

were used for the Lower Oxford Clay.

Ground Water Table

Piezometers were installed at various locations around the excavation to monitor changes of ground water pressure as the face advanced. In Figure 17 are plotted typical piezometric levels recorded in three piezometers installed at different elevations in a group alongside reference point 36 in the centre line section (Figure 12).

The levels are seen to drop consistently as the face of the excavation advances, due presumably to a combination of draw down and dilation of the clay caused by stress relief. The most notable feature of the observations is the difference between the piezometric levels recorded at the three elevations, the deepest piezometer having the lowest level. A possible explanation is that the lower piezometric heads near the base of the face result from dilation associated with strong basal shearing.

For the purposes of the ensuing MBPSSF analysis maximum and minimum water table levels were considered:

H_w (max.) = 27 m (above pit base) (35.0m O.D.)
H_w (min.) = 15 m (above pit base) (23m O.D.)

Ground Movements

Very extensive observations of ground movement were made during this study, using precise surveying, photogrammetry, horizontal extensometers, inclinometers and vertical extensometers.

These measurements showed that large horizontal displacements were occurring with little or no surface extension, indicating that the ground for some distance ahead of the excavation was moving forward as a block and probably sliding on bedding planes close to the base of the pit. A close examination of the face revealed that some overthrusting was taking place,

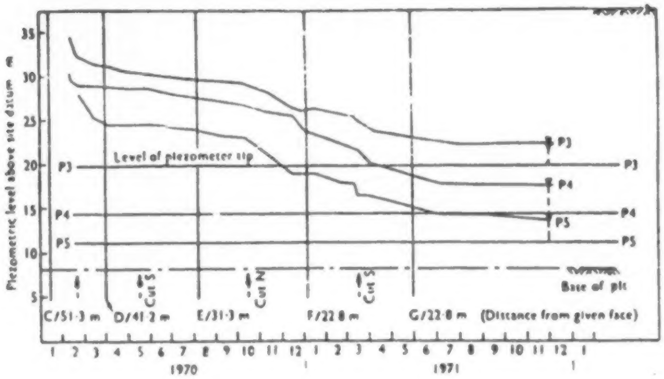
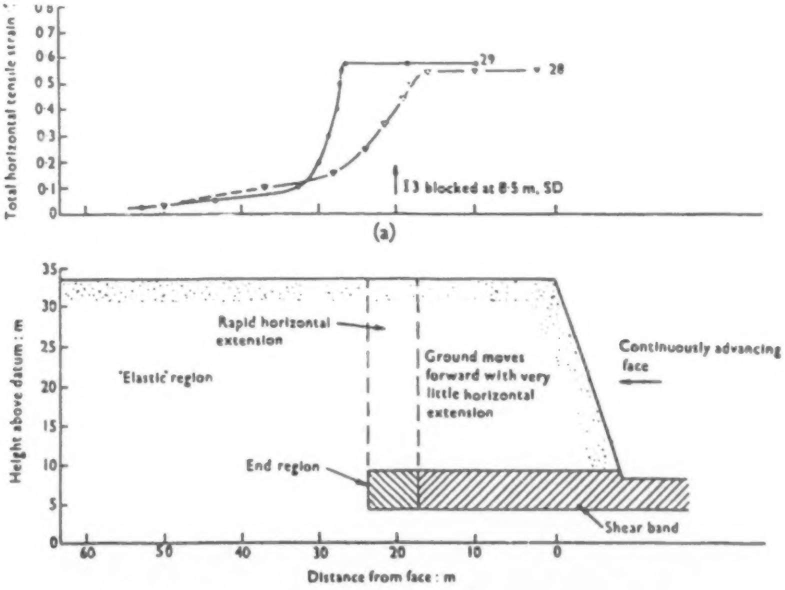


FIG 17 Variation of piezometric levels with time on the centre line of the face showing the relationship with face position



(a)

(b)

FIG 18 (a) Variation of total horizontal surface strain with distance from advancing face (derived from Fig. 20(a)), (b) Interpretation of the surface strain distribution derived from the observations on point 28 especially on one very prominent bedding plane extending along the full length of the face at a height of 1.6m above pit bottom.

For the purposes of the MBPSSF analysis the pit base was taken as being at 29m below ground surface with the failure plane at 1.6m above the pit base; i.e. H=27.4m.

Shear Band Propogation

Burland et al suggest that the mode of failure is one of "shear band propogation". This will be explained in more detail. Figure 18 (a) shows the distribution of total horizontal tensile strain derived from the movement of points 28 and 29 (Figure 12). As the face advances towards a given point in the surface the tensile strain increases slowly at first, then for a short distance it accelerates sharply and thereafter little or no further strain takes place as the face continues to advance.

The distribution of horizontal strain shown in Figure 18 (a) is believed by Burland et al to reflect the existence and mode of propogation of a horizontal shear band near the base of the excavation. Bjerraum (3) discussed the mechanism of progressive failure in clays and clay-shales and concluded that there is a risk of progressive failure in heavily overconsolidated plastic clays like the Oxford Clay under conditions which are similar to those thought to exist at the Saxon pit, namely:

(a) high internal stresses in the clay which are large enough to produce shear stress concentrations in front of an advancing shear band which exceeds the peak shear strength;

(b) the prescence of sufficient recoverable strain energy in the clay to cause relatively large strains on the failure surface and allow the shear strength on this to drop from peak to residual;

(c) brittle clay which shows a large and rapid decrease in shear strength with strain after the peak strength has been mobilized; shear box tests of

Oxford clay taken from near the base of the face and sheared in the direction of bedding show an exceptionally brittle behaviour, a large drop from peak to near residual values occurring after only 3 or 4 mm displacment.

Bjerrum (3) also concluded that the development of a continuous shear band along a bedding plane is a typical mode of progressive failure in unweathered clays and further, that, if there is no tendency for the block of material above the shear surface to slide downhill, the progressive failure will come to a halt at a certain distance from the excavation.

The growth of shear bands in heavily overconsolidated clays has been subject to detailed theoretical investigation (7,8,9). Figure 19 illustrates the shear stress distribution along a horizontal shear band emanating from the face of an advancing excavation. The release of horizontal stress at the face of the excavation induces shear stresses some distance away from the face. As the face advances, the shear stress at a given location increases until it reaches the peak value of the shear strength, T_p, along a bedding plane. Relative displacement across the plane is then initiated. As the shear band propogates the relative displacements across the band increase and the shearing resistance falls, eventually reaching the residual value, T_r. The zone near the tip of the shear band along which the shear stress decreases from peak to residual has been termed the "end of region" (8). A large increase in the horizontal tensile strain occurs in the material above the end region owing to the rapid decrease in stress along it. Behind the end region along the fully developed shear band the shear stress is constant. However, in order to overcome the residual shear resistance a steady decrease in horizontal stress occurs towards the excavation face resulting in horizontal tensile strain as shown in Figure 19.

Burland et al then proceed to interpret their measurements based on these concepts and show that they are compatible with these ideas.

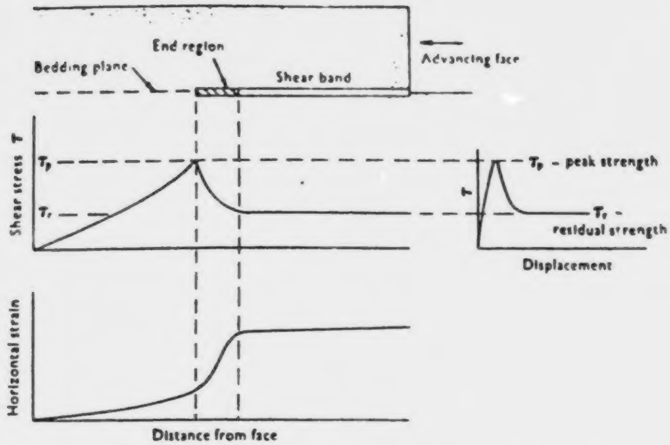

End region
Bedding plane
Shear band
Advancing face
Shear stress τ
τ_p
τ_r
τ
τ_p – peak strength
τ_r – residual strength
Displacement
Horizontal strain
Distance from face

FIG19 Distribution of shear stress and horizontal strain during propagation of shear band

Comparison of "Shear Band Propogation" with Multiple Block Plane Shear Slope Failure

Clearly the mechanism of shear band propogation is possible and it is not the intention of the authors to query its validity. However, study of the results reported by Burland et al raise some questions which lead the authors to believe that the same results could be interpreted by considering the mode of failure to be one of multipe block plane shear slope failure.

The sudden acceleration and subsequent levelling of the tensile strain between points 28 and 29 (Figure 12) attributed by Burland et al to propogation of the shear band could equally well be interpreted as an opening up of the major vertical joint shown in Figure 12 to exist between these two points. i.e. this would be compatible with a MBPSSF mode with the peak shear stress on the shear plane being overcome, and the joint opening up. Stabilization would subsequently occur due to relief of water pressure as this joint opens and via drainage along the shear plane.

It is also of interest to note that beyond the end region, towards the face, Burland et al consider the shear plane to have residual strength. If this is the case then, with the water tables reported, then it can easily been shown that this block would be unstable with c_r and ϕ_r at the residual values of 3.5 kN/m^2 and 13^o respectively, even at the lowest water table level reported. Whereas, it will be shown later, at the lower water table levels using MBPSSF analysis and peak strength values this block would be stable. Burland et al completely ignore the influence of these water pressures in their analysis.

The development of a "shear band propogation" zone as described in this paper and by Bjerrum is only possible when there is a significant stress relief horizontally. Such stress relief is highly likely to occur in overconsolidated clays, however this mechanism would not explain similar failures in relatively stress free rocks or soils. Such stress relief would also assist in MBPSS failure but its absence does not preclude this mechanism.

It is also interesting to speculate whether the major joint set almost parallel to the face is pre-existing or whether it might be the result of multiple block plane shear slope failure. Unfortunately Burland et al do not report on whether such joint sets exist at a greater distance than 250 m from the pit face; consequently no conclusion can be drawn with respect to this speculation.

Having made the above comments it is clearly important to analyze the MBPSSF case to see whether this mode of failure could also explain these results.

Multiple block plane shear failure analysis

Figures 20 (a) and 20 (b) show the cross section given in the Burland et al paper and the geometry considered in the following MBPSSF analysis. It is assumed in this analysis that the shear plane lies at a horizon 1.6 m above the pit bottom, that the slope height (above the shear plane) is 27.4 m, and the slope angle is 72°. The tensile strength of the clays is taken as O kN/m^2 and the peak strength parameters in the lower Oxford Clay were taken as:

$c = 172\ kN/m^2$
$Q = 28^o$

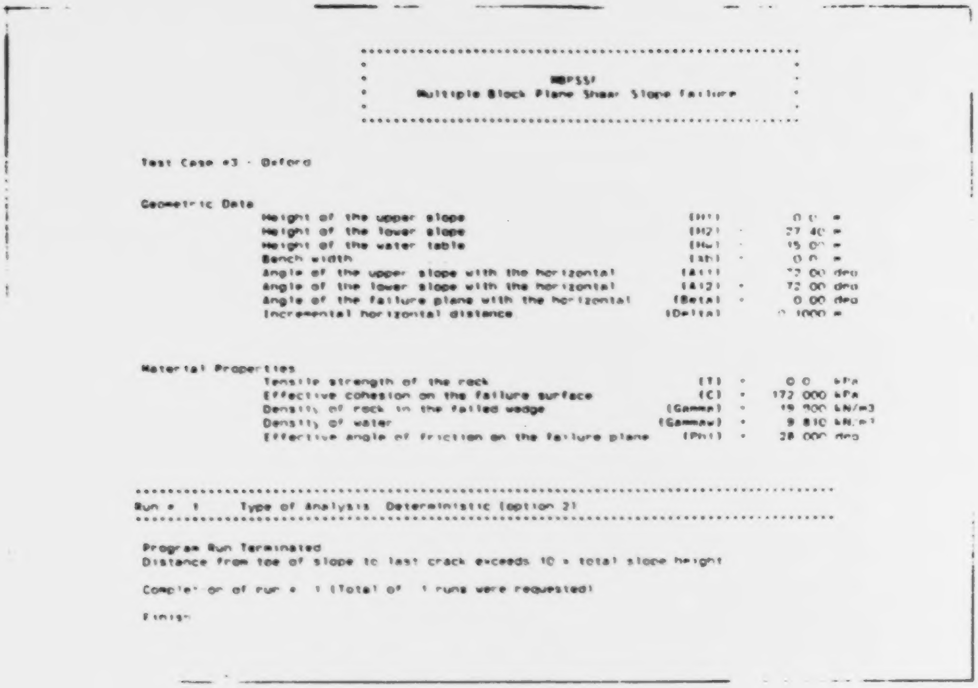
Two analyses were performed, one with the water table $H_w = 15$ m, the other with $H_w = 27$ m.

Tables 17 and 18 list the input values and the results for the first few cracks. Table 19 summarises the upper and lower bound solutions for each use.

Discussion

It is seen from the results of these analyses that, at the lower water table level selected ($H_w = 15$ m) the slope is completely stable with a large safety factor (94). At the maximum water table level ($H_w = 27$ m), the

TABLE 17



```
              ****************************************************
              *                                                  *
              *                      MBPSSF                      *
              *      Multiple Block Plane Shear Slope failure    *
              *                                                  *
              ****************************************************

Test Case #3 - Oxford

Geometric Data
            Height of the upper slope                        (H1)   =     0.0  m
            Height of the lower slope                        (H2)   =    27.40 m
            Height of the water table                        (Hw)   =    15.00 m
            Bench width                                      (bh)   =     0.0  m
            Angle of the upper slope with the horizontal     (A1)   =    72.00 deg
            Angle of the lower slope with the horizontal     (A2)   =    72.00 deg
            Angle of the failure plane with the horizontal  (Beta)  =     0.00 deg
            Incremental horizontal distance                (Delta)  =   0.1000 m


Material Properties
            Tensile strength of the rock                      (T)   =     0.0  kPa
            Effective cohesion on the failure surface         (C)   =  172.000 kPa
            Density of rock in the failed wedge           (Gamma)   =   19.900 kN/m3
            Density of water                             (Gammaw)   =    9.810 kN/m3
            Effective angle of friction on the failure plane  (Phi) =   28.000 deg


*******************************************************************************
Run # 1     Type of Analysis  Deterministic (option 2)
*******************************************************************************

Program Run Terminated
Distance from toe of slope to last crack exceeds 10 x total slope height

Completion of run # 1 (Total of  1 runs were requested)

Finish
```

TABLE 19

```
                ..........................................................
                .                                                        .
                .                        MBPSSI                          .
                .        Multiple Block Plane Shear Slope Failure        .
                .                                                        .
                ..........................................................


Test Case #3   Oxford


Geometric Data
                Height of the upper slope                              (H1)   =      0 0  m
                Height of the lower slope                              (H2)   =     27 40 m
                Height of the water table                              (Hw)   =     27 00 m
                Bench width                                            (Xb)   =      0 0  m
                Angle of the upper slope with the horizontal          (Ai1)   =     72 00 deg
                Angle of the lower slope with the horizontal          (Ai2)   =     72 00 deg
                Angle of the failure plane with the horizontal       (Beta)   =      0 00 deg
                Incremental horizontal distance                      (Delta)  =    0 1000 m


Material Properties
                Tensile strength of the rock                            (T)   =      0 0   kPa
                Effective cohesion on the failure surface               (C)   =    172 000 kPa
                Density of rock in the failed wedge                 (Gamma)   =     19 900 kN/m3
                Density of water                                   (Gammaw)   =      9 810 kN/m3
                Effective angle of friction on the failure plane      (Phi)   =     28 000 deg


.............................................................................................
Run #  1     Type of Analysis  Deterministic (option 2)
.............................................................................................


 Solution number  1    Crack number  1        (Lower limit)
   Factor of Safety                                                                                     (SF)   =     0.9965
   Weight of failed wedge between cracks  0 and  1                                                       (W)   =   4768 27 kN
   Total area of the failure plane, of unit depth, between cracks  0 and  1                             (At)   =     13 20 sq m
   Total uplift force due to water pressure acting on the failure plane between cracks  0 and  1         (U)   =   2333 57 kN
   Force applied to the failed wedge by the water in crack  1                                            (V)   =   3575 68 kN
   Resisting force due to tensile strength across the potential crack  1                                 (Y)   =      0 0  kN
   Horizontal distance between cracks  0 and  1                                                     (Kn+1)   =     13 20 m
   Depth of crack  1 below surface                                                                  (Zn+1)   =     27 32 m
   Distance to crack from toe of slope                                                     (SUMKN + Kn+1)   =     13 20 m

   Case A1(a) - HW > B ie   27 00 >    0 00


 Solution number  1    Crack number  1        (Upper limit)
   Factor of Safety                                                                                     (SF)   =     1.0259
   Weight of failed wedge between cracks  0 and  1                                                       (W)   =   4822 82 kN
   Total area of the failure plane, of unit depth, between cracks  0 and  1                             (At)   =     13 30 sq m
   Total uplift force due to water pressure acting on the failure plane between cracks  0 and  1         (U)   =   2359 99 kN
   Force applied to the failed wedge by the water in crack  1                                            (V)   =   3575 68 kN
   Resisting force due to tensile strength across the potential crack  1                                 (Y)   =      0 0  kN
   Horizontal distance between cracks  0 and  1                                                     (Kn+1)   =     13 30 m
   Depth of crack  1 below surface                                                                  (Zn+1)   =     27 40 m

   Distance to crack from toe of slope                                                     (SUMKN + Kn+1)   =     13 30 m


 Solution number  1    Crack number  2        (Lower limit)
   Factor of Safety                                                                                     (SF)   =     0 9962
   Weight of failed wedge between cracks  1 and  2                                                       (W)   =   4961 81 kN
   Total area of the failure plane, of unit depth, between cracks  1 and  2                             (At)   =      9 10 sq m
   Total uplift force due to water pressure acting on the failure plane between cracks  1 and  2         (U)   =   1205 14 kN
   Force applied to the failed wedge by the water in crack  2 ........                                   (V)   =   3575 64 kN
   Resisting force due to tensile strength across the potential crack  2                                 (Y)   =      0 0  kN
   Horizontal distance between cracks  1 and  2                                                     (Kn+1)   =      9 10 m
   Depth of crack  2 below surface                                                                  (Zn+1)   =     27 40 m
   Distance to crack from toe of slope                                                     (SUMKN + Kn+1)   =     22 40 m

   Case D1(a) - HW > B ie   27 00 >    0 00

 Solution number  1    Crack number  2        (Upper limit)
   Factor of Safety                                                                                     (SF)   =     1.0072
   Weight of failed wedge between cracks  1 and  2                                                       (W)   =   5016 33 kN
   Total area of the failure plane, of unit depth, between cracks  1 and  2                             (At)   =      9 20 sq m
   Total uplift force due to water pressure acting on the failure plane between cracks  1 and  2         (U)   =   1218 38 kN
   Force applied to the failed wedge by the water in crack  2..........                                  (V)   =   3575 64 kN
   Resisting force due to tensile strength across the potential crack  2                                 (Y)   =      0 0  kN
   Horizontal distance between cracks  1 and  2                                                     (Kn+1)   =      9 20 m
   Depth of crack  2 below surface                                                                  (Zn+1)   =     27 40 m
   Distance to crack from toe of slope                                                     (SUMKN + Kn+1)   =     22 50 m


 Solution number  1    Crack number  3        (Lower limit)
   Factor of Safety                                                                                     (SF)   =     0.9962
   Weight of failed wedge between cracks  2 and  3                                                       (W)   =   4961 78 kN
   Total area of the failure plane, of unit depth, between cracks  2 and  3                             (At)   =      9 10 sq m
   Total uplift force due to water pressure acting on the failure plane between cracks  2 and  3         (U)   =   1205 13 kN
   Force applied to the failed wedge by the water in crack  3....                                        (V)   =   3575 60 kN
   Resisting force due to tensile strength across the potential crack  3                                 (Y)   =      0 0  kN
   Horizontal distance between cracks  2 and  3                                                     (Kn+1)   =      9 10 m
   Depth of crack  3 below surface                                                                  (Zn+1)   =     27 40 m
   Distance to crack from toe of slope                                                     (SUMKN + Kn+1)   =     31 60 m

   Case D1(a) - HW > B ie   27 00 >    0 00

 Solution number  1    Crack number  3        (Upper limit)
   Factor of Safety                                                                                     (SF)   =     1 0072
   Weight of failed wedge between cracks  2 and  3 ........                                              (W)   =   5016 31 kN
   Total area of the failure plane, of unit depth, between cracks  2 and  3                             (At)   =      9 20 sq m
   Total uplift force due to water pressure acting on the failure plane between cracks  2 and  3         (U)   =   1218 38 kN
   Force applied to the failed wedge by the water in crack  3........                                    (V)   =   3575 60 kN
   Resisting force due to tensile strength across the potential crack  3                                 (Y)   =      0 C  kN
   Horizontal distance between cracks  2 and  3.                                                    (Kn+1)   =      9 20 m
   Depth of crack  3 below surface                                                                  (Zn+1)   =     27 40 m
   Distance to crack from toe of slope                                                     (SUMKN + Kn+1)   =     31 70 m
```

TABLE 19

```
                    ********************************************
                    *                                          *
                    *                 MBPSSF                   *
                    *  Multiple Block Plane Shear Slope Failure *
                    *                                          *
                    ********************************************
```

$H_w = 15$ m

```
Test Case #3 - Oxford

                                          Summary (upper limit)

                                       Distance to crack number
            1        2        3        4        5        6        7        8        9       10       11       12       13       14
Run   1   No Solution found - Factor of safety =   94.052

                                          Summary (lower limit)

                                       Distance to crack number
            1        2        3        4        5        6        7        8        9       10       11       12       13       14
Run   1   No Solution found - Factor of safety =   94.052
```

$H_w = 27$ m

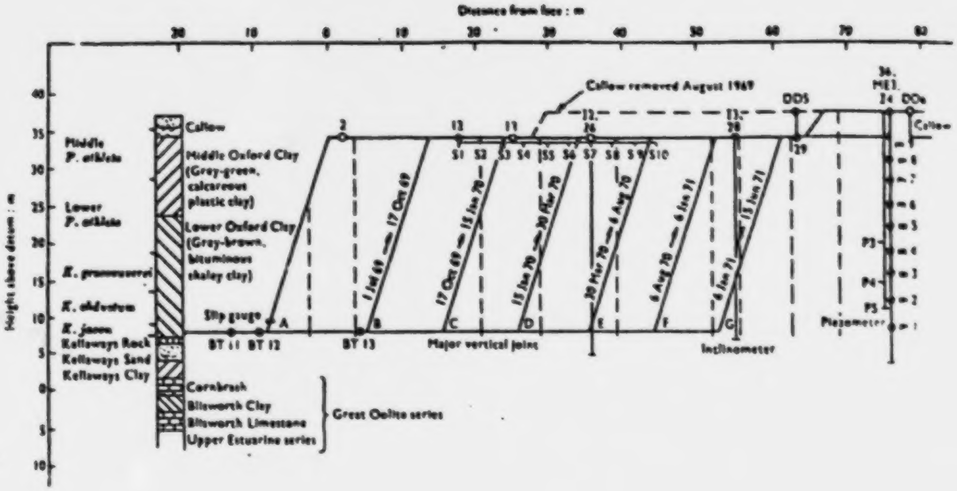
```
Test Case #3 - Oxford

                                          Summary (upper limit)

                                       Distance to crack number
            1        2        3        4        5        6        7        8        9       10       11       12       13       14
Run   1  13.300   22.500   31.700   40.900   50.100   59.300   68.500   77.700   86.900   96.100  105.300  114.500  123.700  132.900

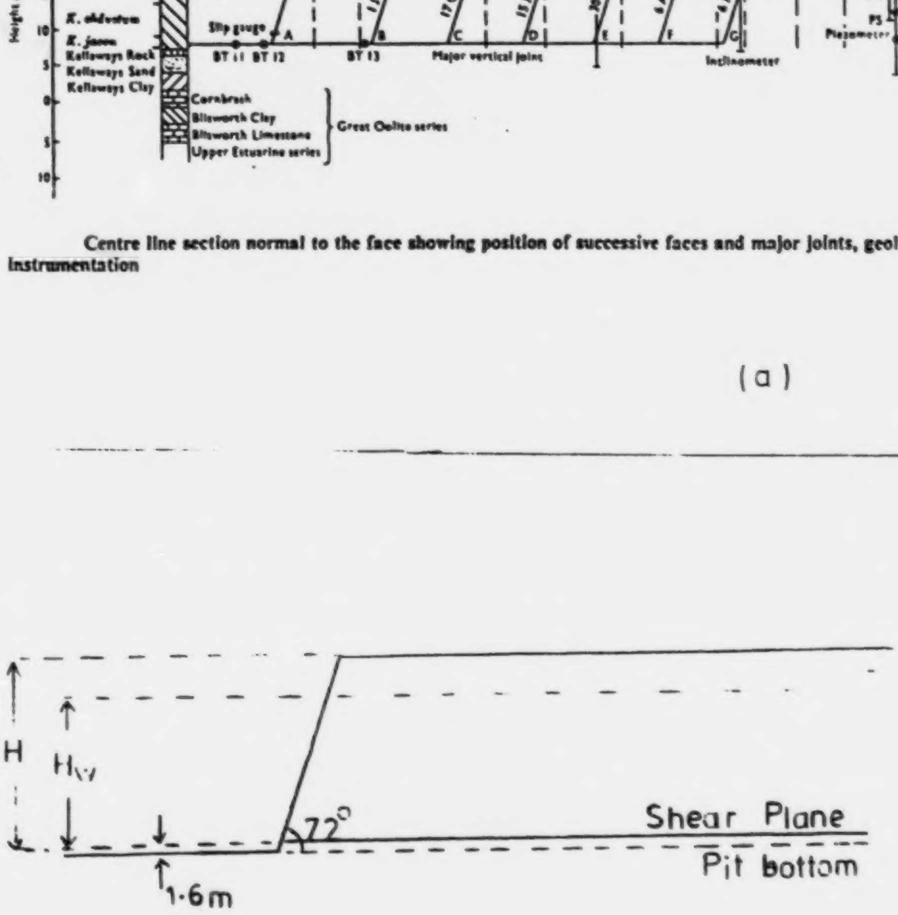
                                          Summary (lower limit)

                                       Distance to crack number
            1        2        3        4        5        6        7        8        9       10       11       12       13       14
Run   1  13.200   22.400   31.600   40.800   50.000   59.200   68.400   77.600   86.800   96.000  105.200  114.400  123.600  132.800
```


Distance from face : m
20
10
0
10
20
30
40
50
60
70
80
Height above datum : m
40
35
30
25
20
15
10
5
0
5
10
Middle P. athleta
Lower P. athleta
K. grossouvrei
K. obductum
K. jason
Kellaways Rock
Kellaways Sand
Kellaways Clay
Callow
Middle Oxford Clay (Grey-green, calcareous plastic clay)
Lower Oxford Clay (Grey-brown, bituminous shaley clay)
Cornbrash
Blisworth Clay
Blisworth Limestone
Upper Estuarine series
Great Oolite series
Slip gauge
A
B
C
D
E
F
G
BT 11
BT 12
BT 13
Major vertical joint
Inclinometer
Piezometer
Callow removed August 1969
2
12
11
22, 26
13, 28
29
DD5
36, HE1, 24
DD6
Callow
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
1 Jul 69 — 17 Oct 69
17 Oct 69 — 15 Jan 70
15 Jan 70 — 20 Mar 70
20 Mar 70 — 6 Aug 70
6 Aug 70 — 6 Jan 71
6 Jan 71
15 Jan 71
P3
P4
P5
m 1
m 2
m 3
m 4
m 5
m 6
m 7
m 8
m 9

Centre line section normal to the face showing position of successive faces and major joints, geology and instrumentation

(a)


H
H_w
72°
Shear Plane
Pit bottom
1·6m

$H = 27{\cdot}4\,m \quad H_w(max) = 27\,m \quad H_w(min) = 15\,m$

(b)

FIG 20 SIMPLIFIED SECTION FOR MBPSSF ANALYSIS

analysis yields as infinite number of cracks regressing back into the solid with a regular spacing of 9.2 m being achieved well back from the face. (It is interesting to note that this spacing lies in the range 5 - 20 m spacing observed for the major vertical joint set; although whether this is of significance cannot be ascertained).

It is thus clear that at some critical water table level between 15 to 27 m, regressive failure back into the pit wall can be initiated by the mode of multiple block plane shear slope failure. Hence this mode of failure could represent an alternative interpretation of the failures observed in this case study.

3.3 Case history #3: Slope Failure - Highvale (1983)

A slope failure occurred in the spring of 1983 along the highwall of cut 07 of the Highvale mine. The failure occurred prior to the removal of coal from the preceeding cut and was easily accessible for examination and study. A consultant (10) was called in to analyze the failure and to make recommendations for methods to safely mine through this failed zone.

Field Observations

The pit 03 failure (Figures 21 and 22) took place in May 1983 along the highwall of cut 07 near the east end of the pit betwen eastings -2900 m and -3200 m. The centre of gravity of the slide lies at easting -3050 m approximately. The volume of the slide was estimated by the consultant to be approximately 37,000 m^3. The highwall was cut at an angle of approximately 40^o prior to failure. After failure the slope had an average angle between 24^o and 27^o.

The limits of the slide and the traces of numerous arcuate tension cracks were mapped and are shown in Figure 21. Particular note was taken of section 2-2 (Figure 21) where there is a sequence of arcuate semi-parallel

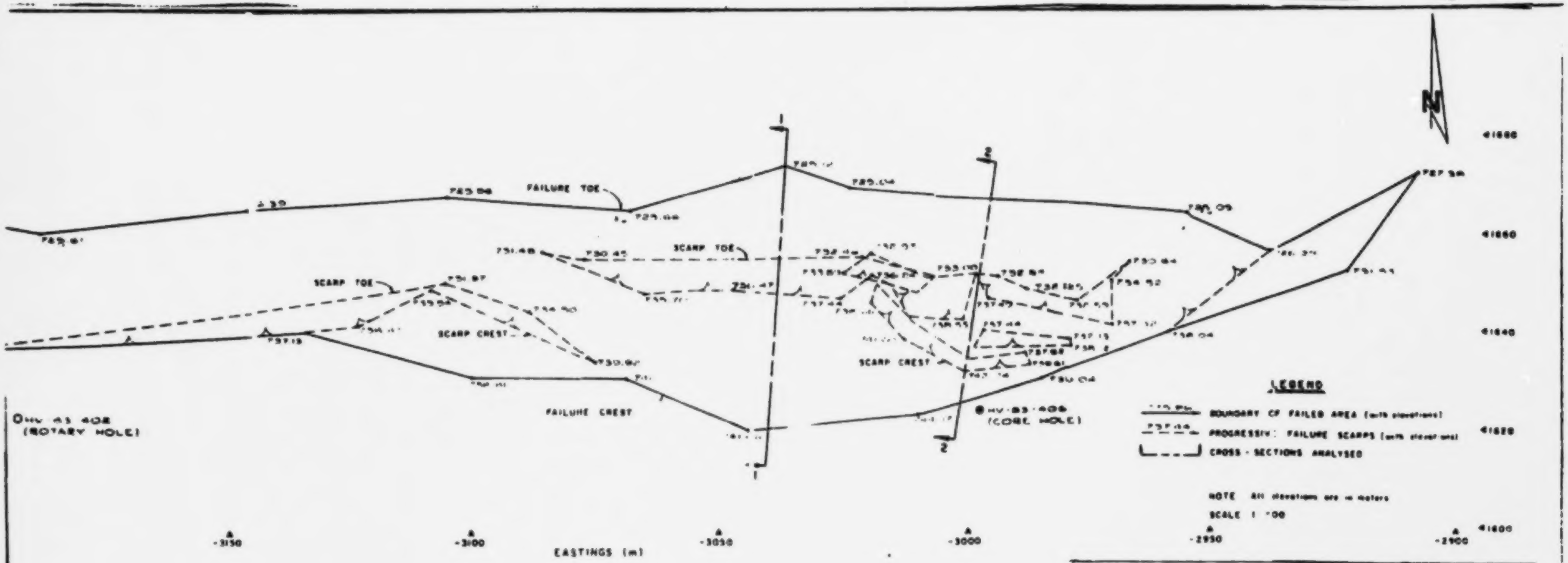

N
FAILURE TOE
SCARP TOE
SCARP TOE
SCARP CREST
SCARP CREST
FAILURE CREST
725.06
725.04
727.98
731.48
730.45
731.97
737.15
730.04
738.04
1
1
2
2
HV-83-406 (CORE HOLE)
HV-83-408 (ROTARY HOLE)
41660
41650
41640
41620
41600
-3150
-3100
-3050
-3000
-2950
-2900
EASTINGS (m)
LEGEND
BOUNDARY OF FAILED AREA (with elevations)
PROGRESSIVE FAILURE SCARPS (with elevations)
CROSS - SECTIONS ANALYSED
NOTE All elevations are in meters
SCALE 1 : 00

FIG. 21

PLAN OF FAILURE ZONE

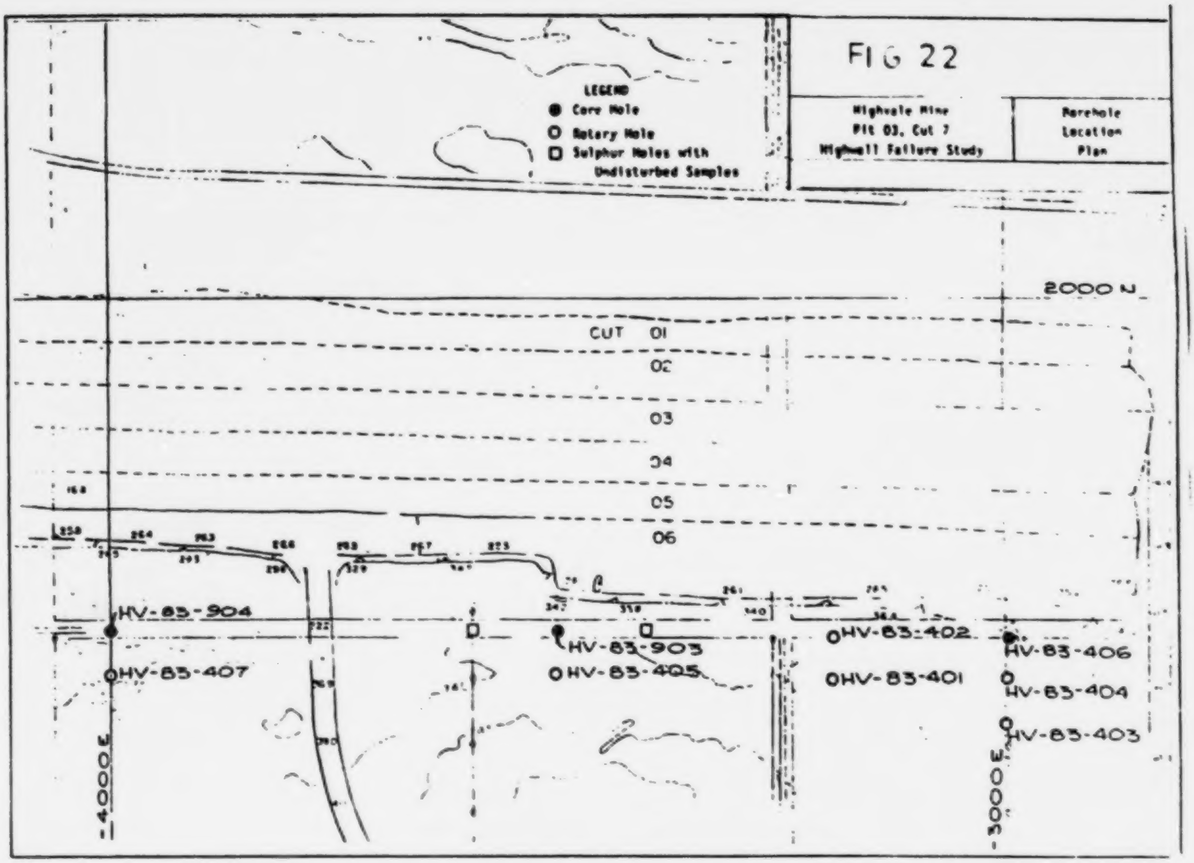

LEGEND
● Core Hole
○ Rotary Hole
☐ Sulphur Holes with Undisturbed Samples
2000 N
CUT 01
02
03
04
05
06
HV-83-904
HV-83-407
HV-83-903
HV-83-405
HV-83-402
HV-83-401
HV-83-406
HV-83-404
HV-83-403
-4000 E
-3000 E

FIG 22

Highvale Mine
Pit 03, Cut 7
Highwall Failure Study

Borehole
Location
Plan

SHEAR STRENGTH PARAMETERS

Soil Type	Soil No.	ϕ'	c'
Friable Sandstone	1(P)	38.0°	0.0
Partially Weathered Sandstone	2(P)	40.0°	0.0
Clay Shale/Mudstone	3(P)	34.0°	48.0
Bentonitic Clay	4(P)	25.0°	24.0
Carbonaceous Shale	5	--	--

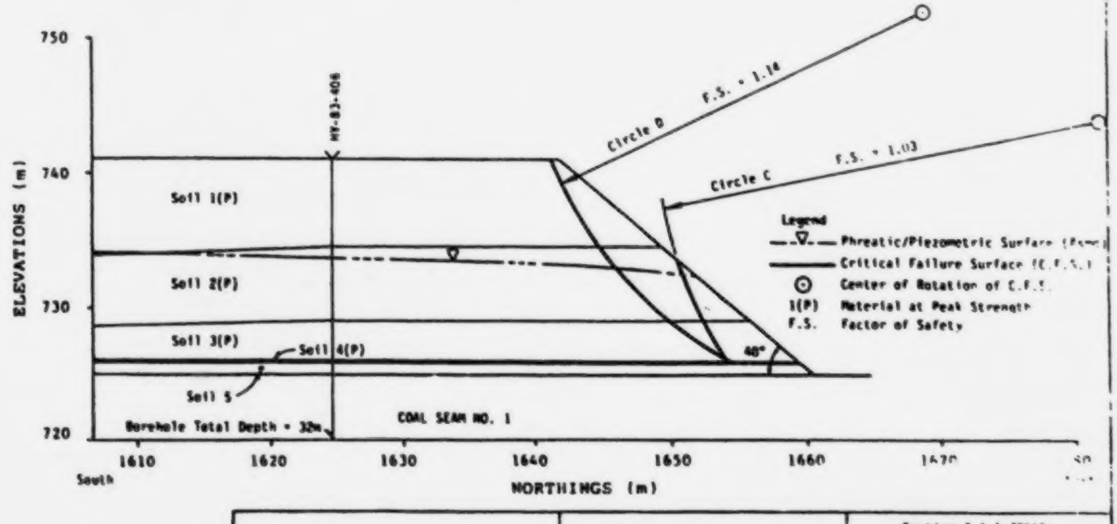

750
740
730
720
ELEVATIONS (m)
HV-83-406
Soil 1(P)
Soil 2(P)
Soil 3(P)
Soil 4(P)
Soil 5
COAL SEAM NO. 1
Borehole Total Depth = 32m
Circle D
F.S. = 1.14
Circle C
F.S. = 1.03
40°
Legend
Phreatic/Piezometric Surface
Critical Failure Surface (C.F.S.)
Center of Rotation of C.F.S.
1(P) Material at Peak Strength
F.S. Factor of Safety
1610
1620
1630
1640
1650
1660
South
NORTHINGS (m)

FIG 23

Highvale Mine - Pit 03, Cut-07
Highwall Failure Study

Section 2-2
Back Analysis of Pre-
Slope Geometry (Cu

or nested tension cracks extending "sub-parallel" to the face. These features indicated to the consultant that the bench had failed in a series of slices defined as a progressive failure mode. Figure 21 also records the position of borehole HV-83-406 which was drilled to define the subsurface geological conditions within the slide and to provide samples for laboratory testing.

Other field observations made in August 1983, indicated that there was a component of rotation to the movement of individual slides (back tilted blocks). In addition clay partings throughout the sandstone gave evidence of shear movement parallel to the beds as indicated by fresh slickensides within and parallel to bedding. All failure movements took place above coal seam #1 and, in the toe area, where the slide debris had been pushed over the coal, the movement appeared to be planar rather than rotational. Consequently, it was concluded that the geometries of the failure surfaces were compound ones comprised of both circular and planar surfaces (e.g see Figure 23).

Ground water data

Hole # HV-83-406 was saturated to a depth of 3.8 metres below the collar elevation. This however was concluded by the consultant not to be representative of the local water table because of insufficient time for the water level to reach equilibrium conditions after drilling.

Piezometer data from approximately 200 m southwest of the slide zone were used to extrapolate the position of the water table in the slide area at the time failure was initiated, as shown in Figure 23. ($H_w \sim 8.0$ m)

Local stratigraphy

The geological log for borehole HV-83-406 show the site to have approximately 1 metre of till underlain by a brown, very friable, fine to medium grained sandstone (identified as soil #1). It is locally bedded with very thin shaly partings; iron oxide is common.

This, in turn, is underlain by a partially weathered sandstone (soil #2); it is a light gray, salt and pepper textured, fine grained sandstone intermixed with clay distributed within the sand beds. Thin, soft, clay partings are commonly present. It is jointed with joints dipping at 50 to 60°. At the base of the unit is a thin but distinctive clay pebble conglomerate.

Soil #3 is a soft clay shale or mudstone lying below the sandstone. Locally it is quite silty and occasionally bentonitic.

Soil layer #4 is a benonitic clay, zoned and very soft. This material lies immediately above a thin coal seam. This layer appears to be the lowest shear strength material in this borehole.

Immediately below layer #4 is a carbonacerous shale which lies above coal seam #1.

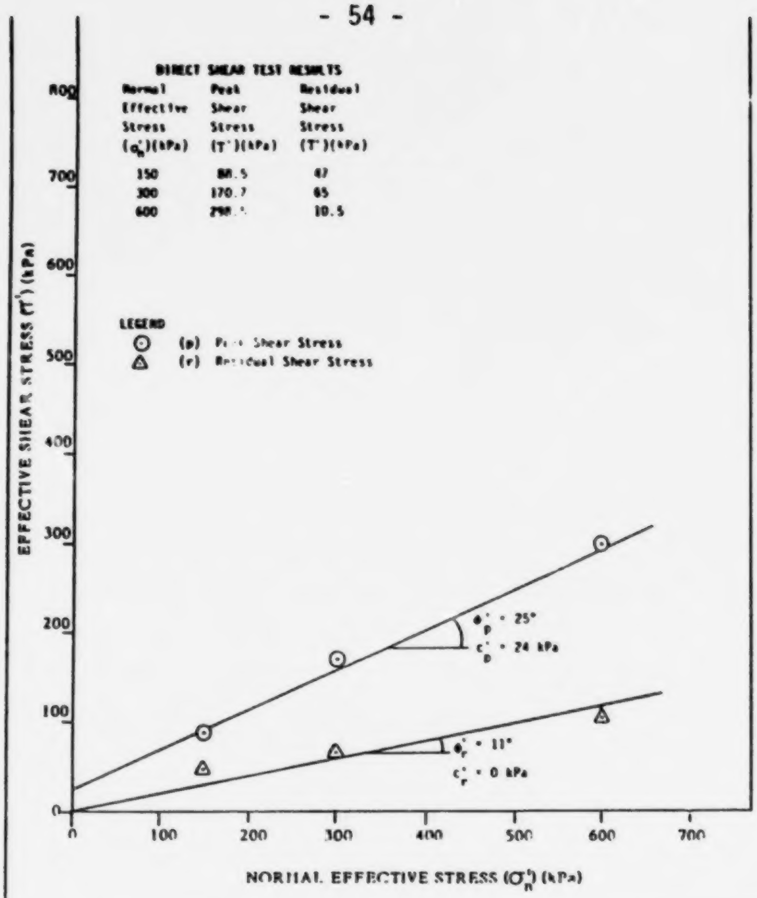
All of these units are essentially flat lying.

Laboratory testing program

Each of these major soil types was sampled for the determination of moisture, density, Attenberg limits and shear strength parameters. Table 20 summarises the results and Figure 24 shows the effective stress Mohr envelope determined for the bentonitic clay (soil 4).

Stability Analysis

The mode of failure was categorized by the consultant as one of the progressive slip, with a composite failure surface incorporating both rotational and translational components of movement. A contributing cause



DIRECT SHEAR TEST RESULTS

Normal Effective Stress (σ'_n)(kPa)	Peak Shear Stress (T')(kPa)	Residual Shear Stress (T')(kPa)
150	88.5	47
300	170.7	65
600	298.[illegible]	10.5

FIG 24

Highvale Mine Pit 03, Cut 07 Highwall Failure Study	Effective Stress Mohr Envelope for Bentonitic Clay (Soil # 4) Hole No. HV-83-406 Sample No. U-10(14.7m to 14.9m)

TABLE 20 SUMMARY OF PHYSICAL PROPERTIES OF MAJOR STRATIGRAPHIC UNITS

Hole No.	HV-83-406									HV-83-906		HV-83-907		Average Moisture Content %
Soil Type	Depth (m)	Moisture Content %	Atterberg Limits			Effective Peak Shear Strengths		Effective Residual Shear Strengths		Depth (m)	Moisture Content %	Depth (m)	Moisture Content %	
			L.L.	P.L.	P.I.	φ'p	c'p(kPa)	φ'r	c'r					
Till												0.5	32.1	[illegible]
												3.[illegible]	42.0	
Soil # 1 Friable Sandstone	1.3	18.5												[illegible]
	2.2	17.1												
	3.2	18.6												
	3.7-4.3	18.7				38.5°	0							
	5.2	18.0												
Soil # 2 Partially Weathered Sandstone	6.9	17.7												[illegible]
	9.2	12.4												
	9.8-10.8	15.1				40.0°	0							
	11.1	14.6												
Soil # 3 Clay Shale and Mudstone	11.8-12.0	26.6	64.9	24.1	40.8	37.0°	66.0	13.0	0	2.0	27.7	4.0	22.8	[illegible]
	11.8	29.7	61.0	31.0	30.0					8.0	19.5	5.6	20.0	
	12.2	26.6	67.2	26.6	40.6					9.0	24.8			
	12.8-13.0	18.6				34.5°	48.0			9.2	26.4			
	13.2	20.5												
	13.4	24.4												
	13.8		67.0	25.3	41.7									
	14.1	16.4												
	14.1		56.1	20.9	35.2									
	14.4-14.6	19.3	59.2	37.5	21.7	48.0°	60.0	13.0	0					
	14.4		62.6	23.9	38.7									
* Soil # 4 Bentonitic Clay	14.7		67.4	23.9	43.5									[illegible]
	14.70 -	51.1	145.8	43.4	102.4	25.0°	24.0	11.0	0					
	14.9													

* Note: Interpreted basal shear zone in back analysis models.

L.L. - Liquid Limit
P.L. - Plastic Limit
P.I. - Plasticity Index

was the thin bentonitic bed (soil #4) and a clay shale horizon (soil #3) above the coal seam. Because the area had experienced a relatively wet spring season, surface water infiltration may have been a contributing factor. The ground water table was estimated at approximately half the height of the slope (Figure 23).

The consultant performed back analyses of the slide zone at two sections defined as 1-1 and 2-2 as shown in Figure 23. In this case study review only section 2-2 will be considered, as the analysis results are very similar with section 1-1.

This back analyses began with the examination of the pre-failed (40°) slopes as originally cut by the dragline. This analysis compared the shear strength values at failure to the peak strengths obtained from the laboratory analyses. The analyses also considered the stability conditions of the final failed slope ($\sim 25^{\circ}$) after all movement had ceased. Bishop's simplified method was used in these back analyses.

Figure 23 illustrates section 2-2 at the initial stage of failure of the slope. A critical slip circle (circle C), with a factor of safety of 1.03, extends halfway up the cut slope. It was postulated that failure would be initiated in the toe area with all materials at peak strength values along the circle. Failure of the toe would result in an oversteepened slope and a softening and consequent reduction of effective shear strengths along the failure plane.

For slip circle C, this oversteepening of the slope, together with a reduction (softening) of the shear strength, would trigger further instability in the form of another slice such as represented by slip circle D.

Slip circle D, involving the full height of this slope with peak effective shear strength values, gave a minimum factor of safety of 1.14. However, the factor of safety drops below 1 when the effective shear strengths of soil layers #3 and #4 became partially softened as they would do with the release of the toe along slip circle C. Additional slices into and up the slope would continue to move until the slope had achieved overall equilibrium (approximately 20° to 25° in this case), with basal shear strength values approaching the residual value.

The consultant then also analyzed the stability of the failed slopes and suggested that control could be achieved by the building of toe buttresses together with a reduction of the overall slope angle from 40° to 35°.

Discussion

With the benefit of hindsight and the experience obtained from observing a similar failure in this same area of the mine, one year later in 1984, the authors' are of the opinion that this failure was one of multiple block plane shear slope failure and not of the progressive compound rotational shear failure proposed and analysed by the consultant, for the following reason:-

In 1984, the observed tension cracks in the crest extended back to over 120 m from the toe of the slope. (i.e. $\sim$ 5 times the slope height). It is difficult to conceive the rotational/basal mode of failure extending back so far since rotation would produce a toe load on the later failed blocks, which might be expected to stabilize them before tension cracking extended so far back. (Note a complete documentation and MBPSSF analysis of the 1984 slide is given as case history #4 in this report).

In addition, regardless of the interpretation of the failure mode, the author's are of the opinion that the proposed control method of building a toe buttress, although technically sound, is not a practical solution. this requires that a buttress up to 10 m wide be built on top of the unmined coal, preventing recovery of this coal at this time and requiring rehandling during the next pass of the dragline in order to recover it. This would significantly increase costs and should be avoided if possible. Further, if the mode of failure is indeed one of multiple block plane shear slope failure the volumes of the failure zone would be significantly larger, requiring a much larger buttress to produce stability.

The authors therefore decided to back analyse this slide, assuming a MBPSS failure mode, to ascertain whether or not the failure would be explained by this mode.

Multiple block plane shear slope failure analysis (deterministic solutions)

(a) Input data

Figure 25 shows the section considered (as per section 2-2). The slope was treated as a single slope case, with:-

$H_2 = H = 15$ m
$i = 40^o$
H_w was varied (see below)

The dip of this bentonitic clay failure plane was taken as -0.06^o (see Appendix 1). The shear properties of the bentonitic clay band were taken as

$c = 24.6$ kPa
$Q = 24.7^o$

based on the results of the consultants tests.

Several deterministic solutions were run, varying the water table height H_w, starting at the approximate water table height $H_w = 8.0$ m assumed by the consultant.

(b) Results

Table 21 shows the crack positions and distances from the "toe" (intersection of the bentonitic clay band with slope face) for deterministic solutions for a range of water table heights ranging from $H_w = 8.0$ to 8.5 m.

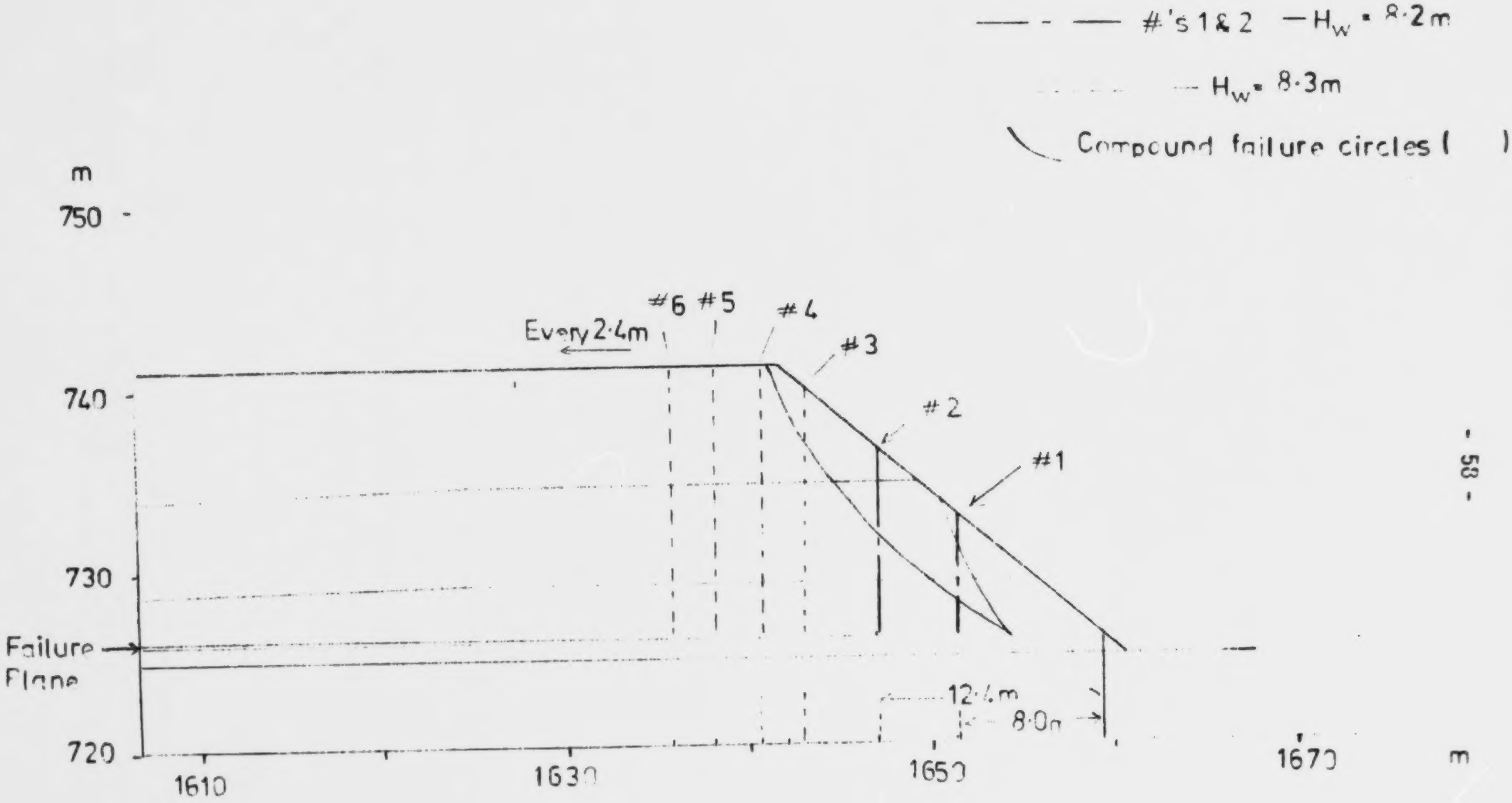

#'s 1 & 2 — H_w = 8·2m
— H_w = 8·3m
Compound failure circles ( )
m
750
740
730
720
Failure Plane
Every 2·4m
#6
#5
#4
#3
#2
#1
12·4m
8·0m
1610
1630
1650
1670
m

FIG 25: MBPSSF ANALYSIS - HIGHVALE (19-3) - DETERMINISTIC SOLUTION

TABLE 21 HIGHVALE (1983) - VARIATION OF H_w - DETERMINISTIC SOLUTIONS

SUMMARY - UPPER LIMIT SOLUTIONS

H_w	Distance of crack number - metres Crack No. 1	2	3	4	5	6	7	8	9	10	11	12	13	14
8.0	7.7	11.9												
8.15	7.9	12.2												
8.20	8.0	12.3												
8.23	8.0	12.4												
8.25	8.1	12.5												
8.27	8.1	12.5	16.3	18.0										
8.30	8.1	12.5	16.3	18.0	20.3	22.6	24.9	27.2	29.5	31.8	34.1	36.4	38.7	41.0
		then every 2.3 m												
8.5	8.4	12.9	16.8	18.7	21.1	23.5	25.9	28.3	30.7	33.1	35.5	37.9	40.3	42.7
		then every 2.4 m												

It is seen from this table that below an H_w of 8.25 m only 2 cracks are formed at approximately 8.0 m and 12.4 m from the "toe". Above H_w = 8.3 m an infinite number of cracks are theoretically formed; the position of the first two being almost identified with the positions at the lower water tables.

Figure 25 shows these crack positions and compares them with the slip cracks determined by the "compound failure analysis" performed previously by the consultants. It is seen that the MBPSSF failure analysis for the first two crack positions agrees quite well with the positions predicted by the compound failure analysis for the same water table levels (8.0 m = H_w). However re-examination of Figure 21 shows that section 2-2 is somewhat exceptional in that it only shows 2 crack sets - any section considered only a few metres either sale of section 2-2 could show up to 6 sets of cracks.

MBPSSF analysis indicates why there is such a variation in the number of crack sets. The assumed water table level of $\sim$ 8 metres is very close to the critical level of $\sim$ 8.27 m where the number of crack sets goes from 2 to infinity ! This indicates just how sensitive this mode of failure is to the water table level.

It was therefore decided to use the probabilistic capabilities of the MBPSSF program to examine the probabilities of crack sets occuring at this critical water table level of 8.27 m.

MBPSSF Probabalistic analysis

The geometrical factors were kept constant as was the assumption that the tensile strength was zero.

The dip of the bentonitic failure plane was assumed to be

- 0.06° with a standard deviation of 0.10°
(This was based on measurements made in 1984 and given in appendix 1)

The variations of c and ϕ used were:

c = 24.6 kPa with standard deviation = 25.6 kPa
Q = 24.7° with a standard deviation = 3.05°

based on the consultants test results (data set 1, Appendix 2).

A total of 99 runs were performed; Table 22 lists the summary of the crack positions (upper limit solution) for each of these runs.

(a) Individual and combined probability of crack sets occurring

The individual probability of a crack set occurring is defined as the probability of a nth crack occurring when the (n-1)th crack has already occurred.

The combined probability of a crack set occurring is defined as the overall probability of the nth crack set occurring and clearly is the product of the individual probabilities.

Table 23 lists the number of runs; the number of runs in which the 1st, 2nd - nth cracks occurred and calculates the individual and combined probabilities.

TABLE 22: HIGHVALE [1983] — H_y = 8·27m PROBABILISTIC SOLUTIONS

```
Test Case #1 - Single Slope - H1=0, H2=H, i1=i2=1, x=0

                                      Summary (upper limit)

                                    Distance to crack number
            1       2       3       4       5       6       7       8       9      10      11      12      13      14
Run  1    9.200  13.700
Run  2    7.600
Run  3    9.000  13.700
Run  4    9.800  14.000
Run  5   11.500  16.400
Run  6    6.800
Run  7    6.000   9.700  13.000  16.100
Run  8    4.800   8.200  11.100  13.900
Run  9    No Solution found - Factor of safety =   48.955
Run 10   10.100
Run 11    7.900  12.000  15.600
Run 12    No Solution found - Factor of safety =   85.503
Run 13    9.000  13.500  17.400  19.100
Run 14   11.200  16.700  19.700
Run 15    6.000   9.800  13.200  16.400
Run 16    6.000   9.800  13.200  16.400  17.900
Run 17   15.000  18.700  22.600  26.500  30.400  34.300  38.200  42.100  46.000  49.900  53.800  57.700  61.600  65.500
Run 18   11.300
Run 19   13.500  17.700
Run 20   11.900  17.300  20.100
Run 21    No Solution found - Factor of safety =  114.787
Run 22    8.300  12.500
Run 23    7.000  11.200  14.900
Run 24   11.200  16.000  18.100
Run 25   13.100
Run 26    7.000  11.500  15.400
Run 27    7.700
Run 28    6.700  11.000  14.800
Run 29   16.300
Run 30    8.200
Run 31   11.600  16.200
Run 32    6.700  10.500  13.900
Run 33    8.700  13.000
Run 34   13.200
Run 35    4.800   8.600  12.000  15.200
Run 36    9.300  14.000
Run 37   11.800  17.800  21.400  25.400  29.400  33.400  37.400  41.400  45.400  49.400  53.400  57.400  61.400  65.400
Run 38    6.200
Run 39    6.700  10.800  14.400
Run 40    7.300  11.200
Run 41    3.200
Run 42    5.200
Run 43    6.000
Run 44    6.700  10.600  14.100
Run 45    4.100   7.200   9.800
Run 46    8.000  12.100
Run 47   17.500  21.300  25.600  29.900  34.200  38.500  42.800  47.100  51.400  55.700  60.000  64.300  68.600  72.900
Run 48    9.100  13.600
Run 49    9.700  13.900
Run 50   12.600  17.000  18.600
Run 51    5.200   8.900
Run 52    5.100
Run 53   11.300  16.200
Run 54   11.000
Run 55    6.300  10.300  13.900
Run 56    6.400  10.700  14.800
Run 57    6.800  10.800
Run 58   13.900
Run 59    6.100   9.800  13.100  16.200
Run 60    5.400   8.900  12.000
Run 61   12.800  17.500  19.400
Run 62   11.700  16.600
Run 63   12.900
Run 64    5.100   8.700  11.900
Run 65    No Solution found - Factor of safety =   68.107
Run 66   11.900  16.600
Run 67   17.000  20.900  25.200  29.500  33.800
Run 68   12.000  17.100  19.500  22.500  25.500  28.500  31.500  34.500  37.500  40.500  43.500  46.500  49.500  52.500
Run 69   10.500
Run 70   13.300  17.800  19.500  22.000  24.500  27.000  29.500  32.000  34.500
Run 71    9.100  14.200
Run 72    6.200  10.200
Run 73    4.700
Run 74   12.500
Run 75    9.100
Run 76    6.300  10.300  13.900
Run 77    6.800
Run 78    No Solution found - Factor of safety =   79.064
Run 79    7.400
Run 80    8.400  12.700  16.400
Run 81   13.700
Run 82    4.500   7.700
Run 83    5.200   8.800  12.000
Run 84   12.100
Run 85   24.900  29.400  33.900  38.400  42.900  47.400  51.900  56.400  60.900  65.400  69.900  74.400  78.900  83.400
Run 86    No Solution found - Factor of safety =   84.426
Run 87    5.300   9.300  12.900  16.300  18.300  20.700  23.100  25.500  27.900  30.300  32.700  35.100  37.500  39.900
Run 88   13.500
Run 89   15.400
Run 90    5.200
Run 91   16.500  19.400  22.900  26.400  29.900  33.400  36.900  40.400  43.900  47.400
Run 92    9.600  14.000
Run 93    9.800  14.700
Run 94    8.900  13.400
Run 95    9.700  14.300
Run 96    5.100   8.500
Run 97    5.300
Run 98    5.200   8.900  12.200  15.300
Run 99   11.000
```

TABLE 23 HIGHVALE (1983) - $H_w = 8.27$ m - PROBABILISTIC SOLUTIONS

TOTAL # RUNS = 99

Crack #	Previous # of Runs	# of Failures	Individual Probability	Combined Probability	Mean Position m	s.d m
1st Crack	99	93	93.9%	93.9%	9.21 m	3.75 m
2nd Crack	93 99	63	67.7%	63.6% 63.6%	13.3 m	4.1 m
3rd Crack	63 99	37	58.7%	37.3% 37.3%	16.5 m	5.0 m
4th Crack	37 99	17	45.9%	17.1% 17.1%	21.5 m	6.9 m
5th Crack	17 99	10	58.8%	10.1% 10.1%	28.7 m	7.6 m
6th Crack	10 99	8	80.0%	8.1% 8.1%	32.9 m	8.0 m
> 6 Cracks	8 99	8	100%	8.1% 8.1%		

Figure 26 shows the individual probabilities of each crack set occurring. It is seen that for this case the individual probability of the first crack occurring is 93.9% reducing to 45.9% for the fourth crack set and then rising again to 100% for greater than 6 crack sets. This rise to 100% for a large number of cracks is at first somewhat surprising but is merely a reflection that once away from the variations caused by the slope face, the failure condition for a block for very flat failure planes are identical and if one block fails then an almost identical set of conditions fails the next block - this leads to the theoretical possibility of an infinite number of cracks occurring.

However, of more practical importance is the combined probability which is shown in Figure 27. The combined probability of the first crack set occurring of 93.9 %, for the second crack set it is 63.6%, etc. dropping to 8.1 % for greater than 6 crack sets. i.e. there is a small but finite probability for great than six crack sets occurring.

(b) Probability for the crack positions

From the tabulated results for the crack positions (Table 22) it is possible to determine the mean crack position and its standard deviation for each crack set. This has been done for the first six crack sets. Assuming a normal distribution of crack positions for each set the nomalized density function distribution of crack position can be determined and also the range of crack positions at a given probability level can be derived. This has been done in Figure 28 and Table 24. e.g. There is a 93.9% probability that crack set 1 will occur and there is a 95% probability that if it occurs it will be in a range 1.85 to 16.5 m from the toe (there is a 50% probability that it will be at the mean position 9.2 m from the toe).

Therefore there is a 63.6% probability that a second crack set will occur and there is a 95% probability that it will be between 5.3 to 21.3 m from the toe (there is a 50% probability that it will be at the mean position 13.3. m from the toe).

It is clear from Figure 28 that there is a finite and significant

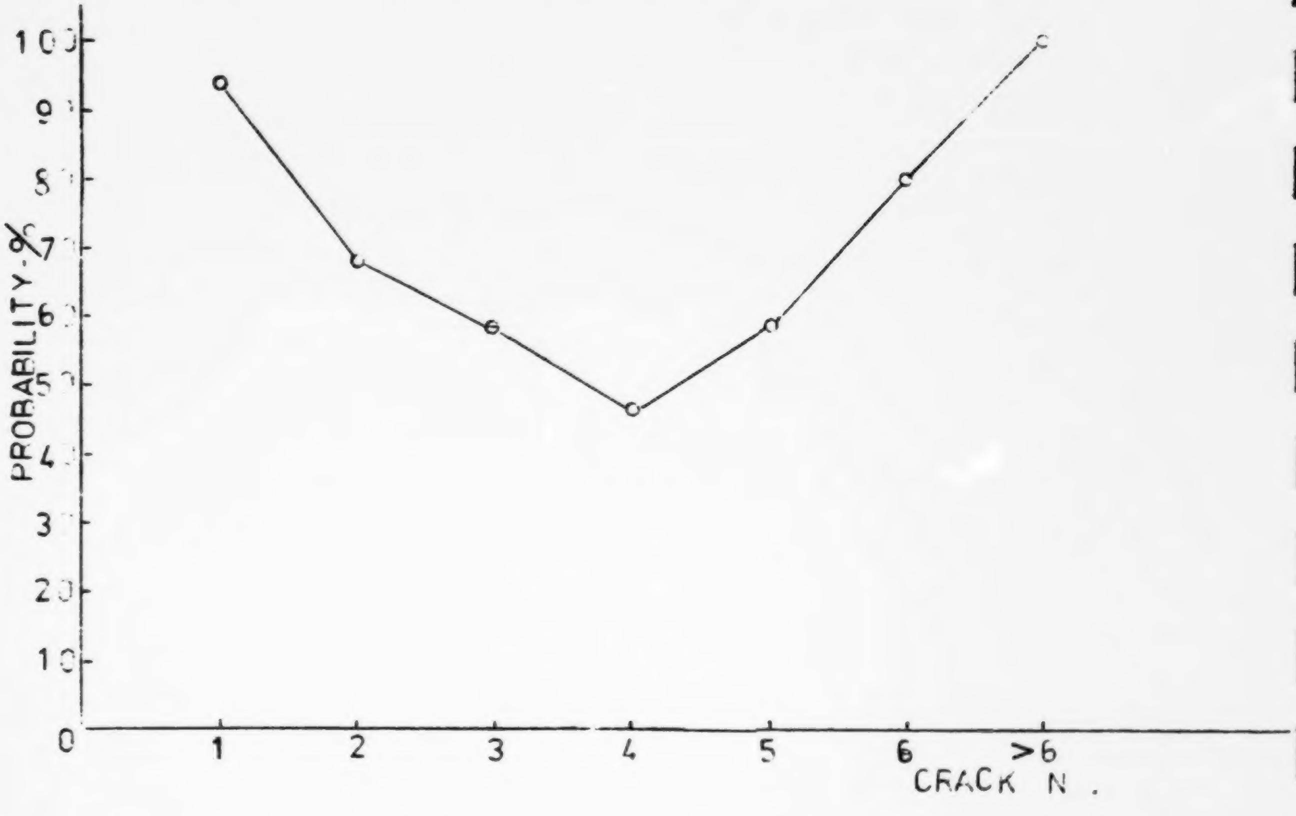


FIG 26: INDIVIDUAL PROBABILITY OF A CRACK OCCURING

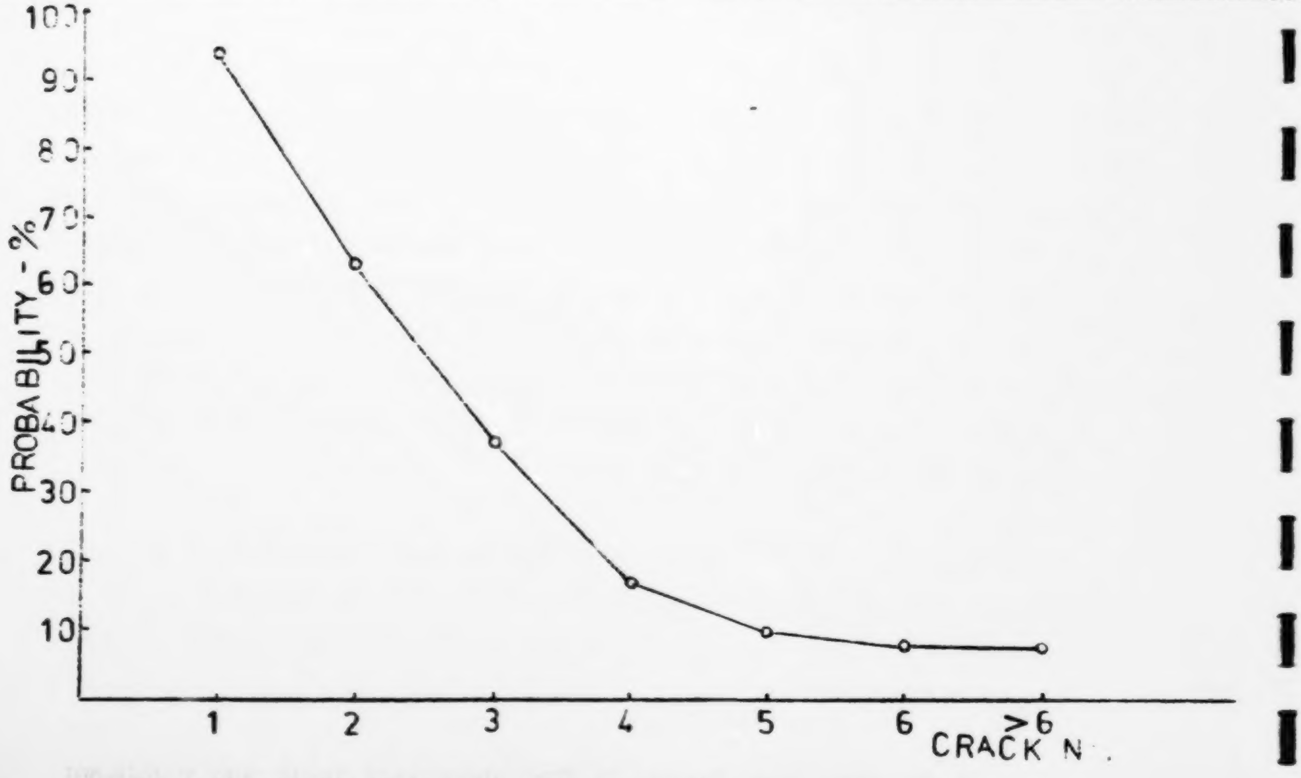


FIG 27: COMBINED PROBABILITY OF A CRACK OCCURING

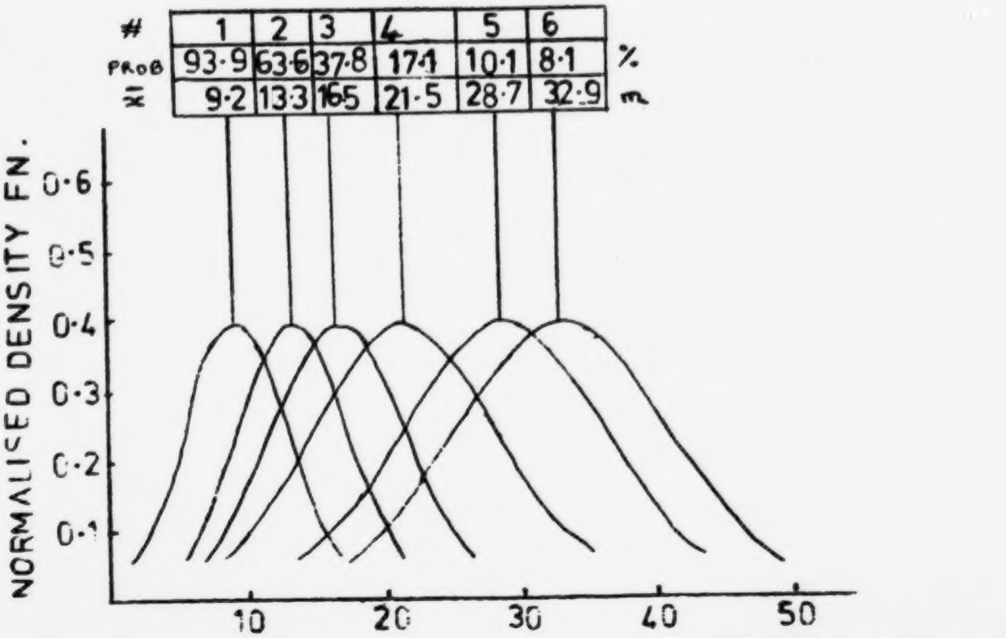


FIG 28: DISTRIBUTION CURVES FOR CRACK POSITIONS -95% PROBABILITY

TABLE 24 RANGE OF CRACK POSITIONS AT 95% PROBABILITY LEVEL

95% PROBABILITY WHEN m = x ± 1.9 bσ

Crack #	Mean Position x m	S.D.	95% Range m	Combined Probability of crack occurring %
1	9.2	3.75	16.6 - 1.85	93.9
2	13.3	4.1	21.3 - 5.3	63.6
3	16.5	5.0	26.3 - 6.7	37.8
4	21.5	6.9	35.0 - 8.0	17.1
5	28.7	7.6	43.5 - 13.8	10.1
6	32.9	8.0	48.6 - 17.2	8.1

probability that the various crack sets can and will overlap. Consequently the value of identifying a first or second or third crack set must be questioned. What is much more important from a practical point of view is the overall extent of the failed zone. This will be considered next.

Probability of the extent of the fracture zone

From Table 22 the mean position and standard deviation of the last crack set occurring was determined. Note: From those runs in which an infinite number of cracks extend to an infinite distance from the toe of the slope, it was assumed that the extent of cracking was limited to 10 times the slope height (i.e. 150 m).

The mean maximum extent of the fracture zone so determined was:-

x = 21.0 m with a standard deviation of 33.6 m (n = 99 runs)

From this, assuming a normal distribution, the probability that the fracture zone extends beyond a value greater than x_i was calculated (using the polynomial approximation approach given in Appendix 1). Figure 29 shows this probability plotted against x_i metres.

e.g. (i) there is a 64% probability that the fracture zone will extend beyond 10 metres from the toe.

(ii) there is a 16.5% probability that the extent of fracturing will extend beyond 50 m from the toe.

It is believed that this is a much more useful analysis for design purposes than the consideration of the probable number of crack sets or the probable position of the cracks. Overall, the bench will be unstable whether it is broken up one or by, say, ten cracks sets; the total extent of the cracked zone is much more important. Hence this latter technique would allow the probability of the unstable portion of the bench to be determined for any particular water table level.

For example in this example, for a water table level of H_w = 8.27 m:-

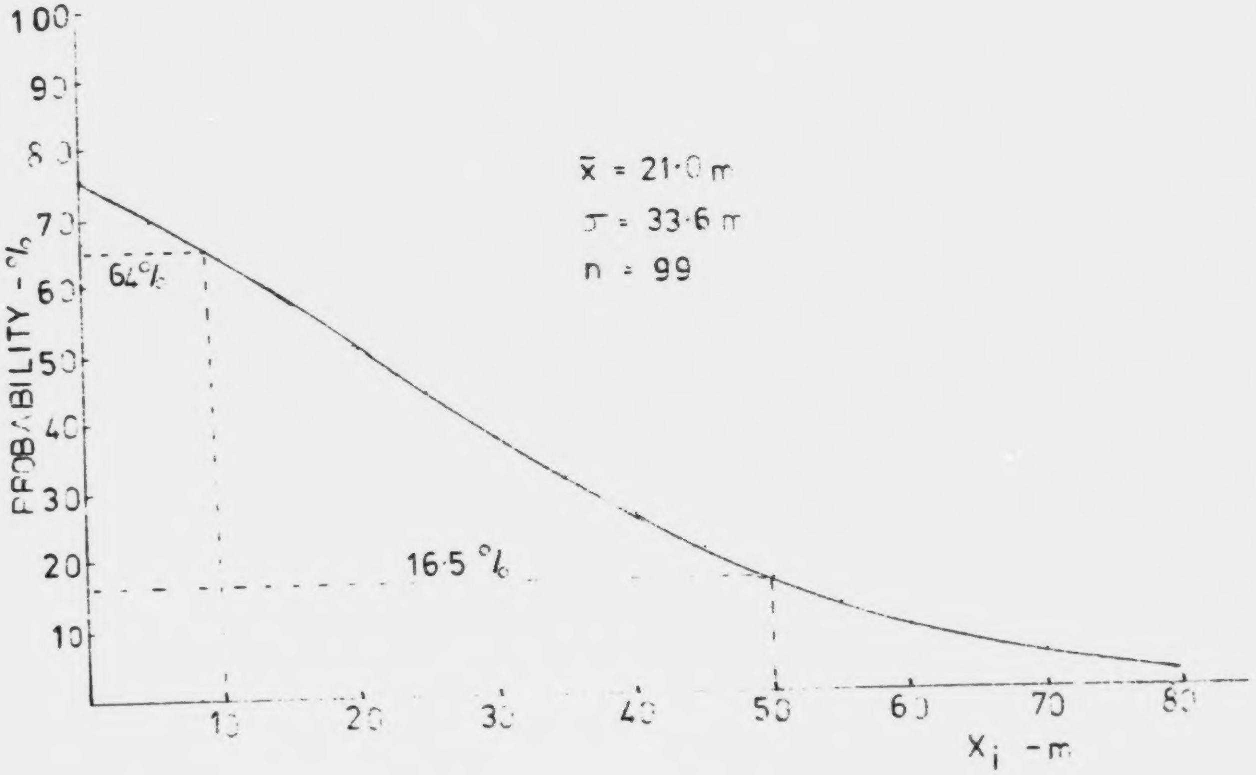


FIG 29 PROBABILITY OF FAILURE EXTENDING BEYOND X_i METRES

(i) the probability that cracking of any sort will occur in very high (93.9%)

(ii) However the probability that the cracking will extend beyond the crest of the slope, onto the dragline working area (i.e. extends beyond 8.7 m) is, from Figure 29, 67%. This is still a probability of failure unlikely to be acceptable for design purposes.

However, other water table levels can be analysed in a similar manner and if management were to deem, for example, that a 10% probability of failure extending beyond the crest was acceptable for operational purposes then the water table level which yielded a 10% probability of failure extending beyond 8.7 m could be determined. This would give a target for taking measures to reduce the water table level to increase the slope stability. It is clear from the analysis that the best potential way to control the stability of this highwall is by drainage to reduce the pore water pressures. However what is not known is whether effective drainage could be achieved in the overlying strata, particularly as it has a large clay content. This will be discussed further following the analysis of the 1984 slope failure at this mine which was fully documented by the authors and is reported as case history #4 in this report.

3.4 Case history No. 4: Slope failure - Highvale (1984)

3.4.1 Description and field observations

In the spring of 1984 the pit wall at Highvale mine failed in a manner that appeared to be multiple block plane shear failure. This failure took place at the east end of pit 03 during cut 9 (see Figure 30). This failure was in exactly the same area of the pit as that documented as case history No. 3. The only difference being that in 1983 the mining was in cut 07 whereas by 1984 it has advanced to cut 09. In addition, in 1984 the failure extended back from the toe a much greater distance than was reported in 1983.

A field team was sent to document the failure and to map the cracking that had occurred. The failed zone extended back from the toe for about 110 m maximum distance (section 5 + 70, Figure 31). Unfortunately the dragline bench had been levelled following the failure but prior to the

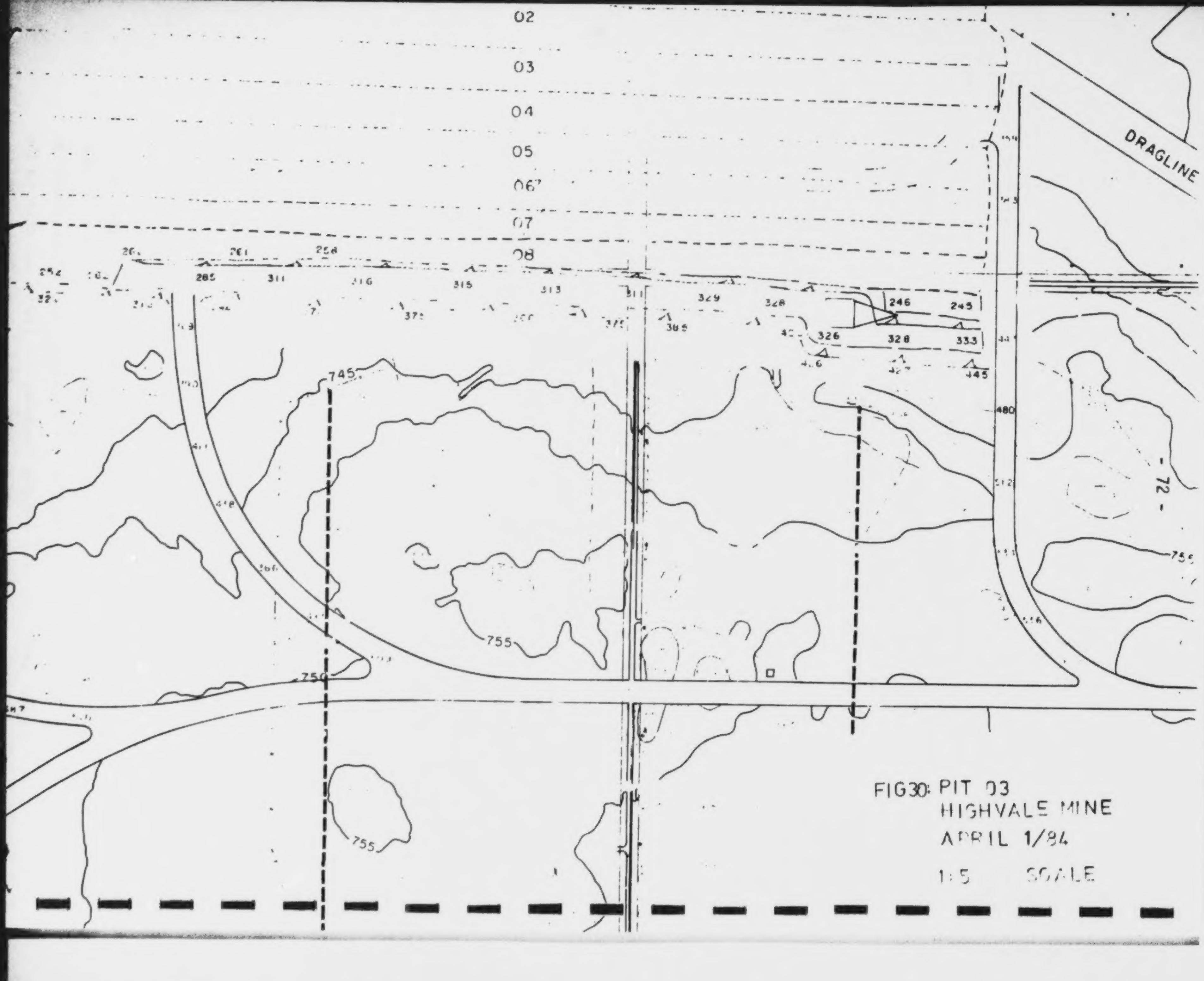

02
03
04
05
06
07
08
DRAGLINE
252
261
258
285
311
316
315
313
311
329
328
246
245
326
328
333
445
480
375
385
745
750
755
755
755
755

FIG30: PIT 03
HIGHVALE MINE
APRIL 1/84
1:5 SCALE

arrival of the field team on site; consequently no observation of cracking could be reliably made on this bench. Even so, at least 11 sets of cracks were observed in the lower and upper slopes and in the crest. However, there was such a multitude of cracks visible that it was virtually impossible to map them all, especially since they would run one into the other. It was also difficult to distinguish or define a tension crack; the very large cracks were obvious but in between were numerous "minor" cracks which might only have been surface drying cracks or which could have been deeper cracks which had not yet opened. The set of photographs in the ensuring plates illustrate those points.

Plate 1 shows an aerial photograph of the failed zone. The transparent overlying to this plate shows the major and a few of the more persistent minor cracks that were traced.

Plate 2 shows a ground level view of the failed zone; crack sets are clearly visible in the upper and lower slopes.

Plate 3 shows the dragline bench. As reported above, this bench had been levelled following the failure and prior to the arrival of the field crew. Nonetheless, as seen in this plate, it appeared that at least one crack set had opened up again.

Plates 4 and 5 show views looking West (plate 4) and East (plate 5) from section 5 + 70 at about 60 m from the toe. A very large number of crack sets are visible which run one into the other and made reliable mapping of all cracks almost impossible.

Plate 6 shows a view of the failed zone taken from within the pit. A crack set in the lower slope is clearly visible. Of importance also is the seepage clearly seen on the coal seam face that is eminating from just above the coal seam and in fact stems from a bentonitic clay band which is believed to be the failure plane. Similar seepage from the clay band is clearly visible in the East end wall of the pit (Plate 8). Plate 7 shows a photograph of this clay band.

Plate 9 shows a failure in the east end wall of the pit that occurred later (this photograph was taken in August 1984). At least 5 sets of vertical cracks are apparent in this photograph.

Plate 10 shows the failed zone in August 1984 when cut 10 had mined through what previously (in April) was the dragline bench. It is clearly seen from the slumping that the tension cracks were almost vertical. It is not believed that additional failure occurred during the mining of cut 10, although it was not possible to be categorically certain of this. This cut was mined in mid summer when the water table was presumably relatively low. Thus this "failure" in August is believed merely to be slumping of the existing fractured blocks created by the failure in the spring.

PLATE I

Plate 2

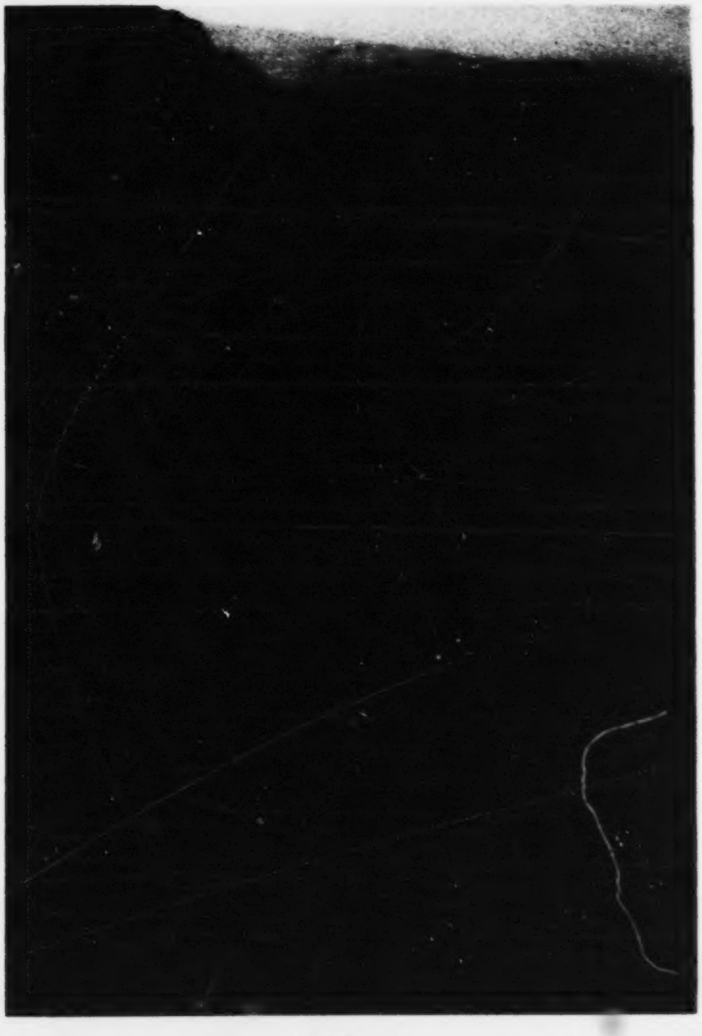


Plate 3

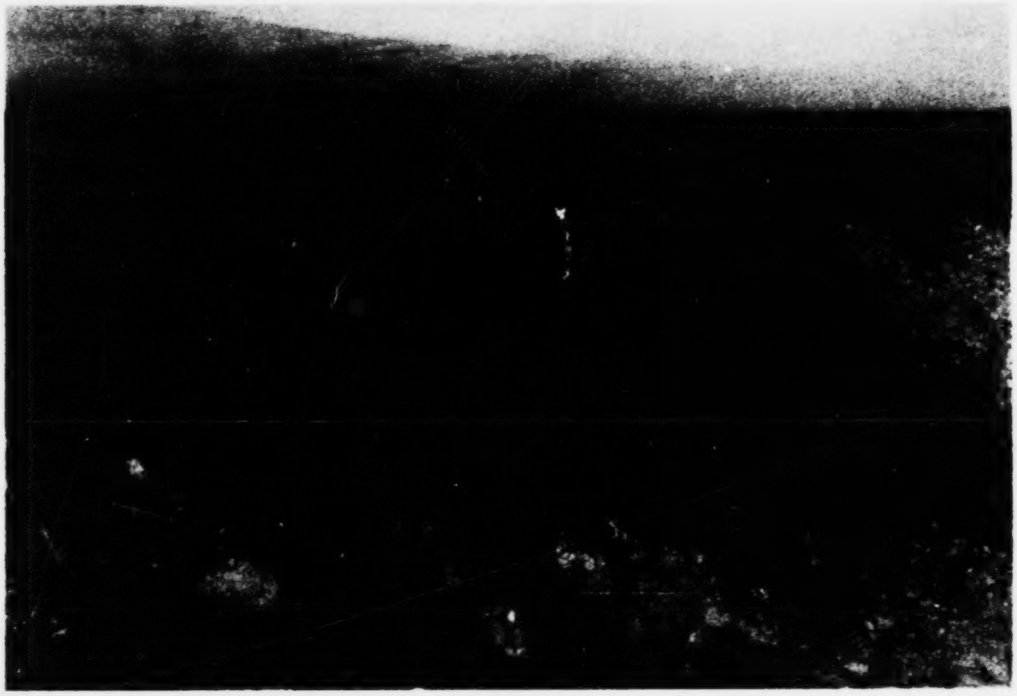


Plate 4

Plate 5

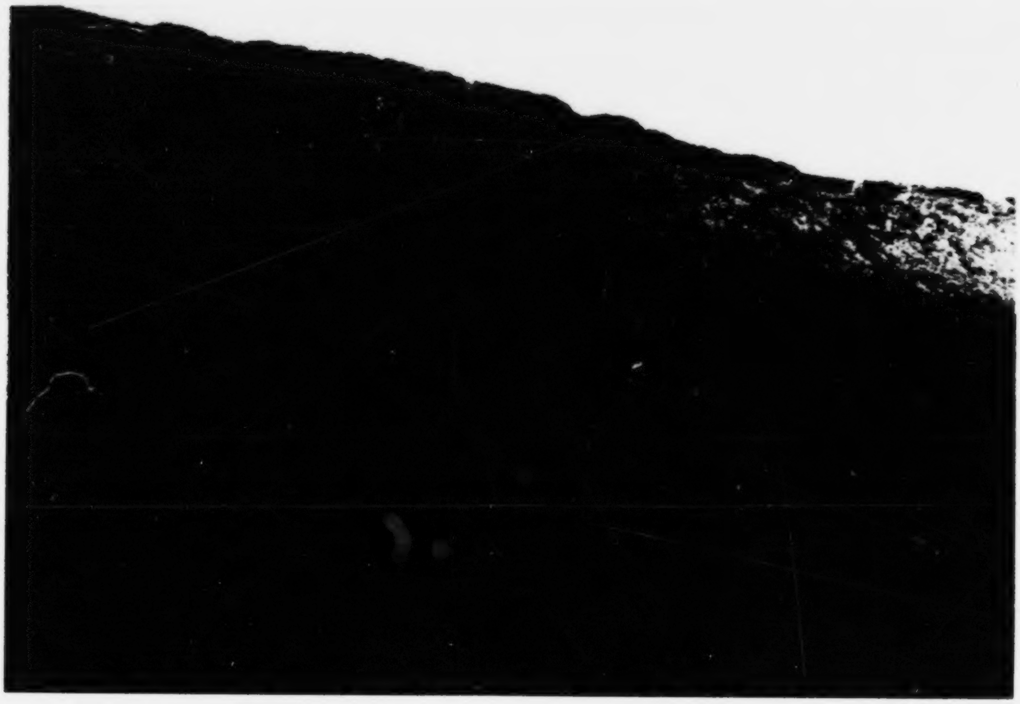


Plate 6

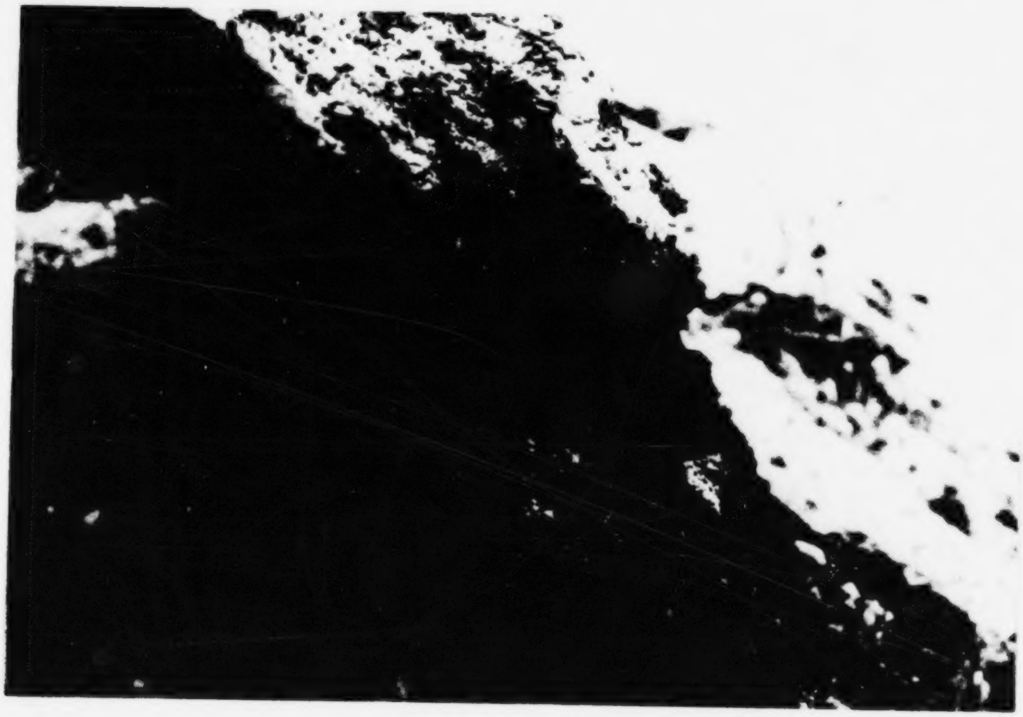


Plate 7

Plate 8

Plate 9

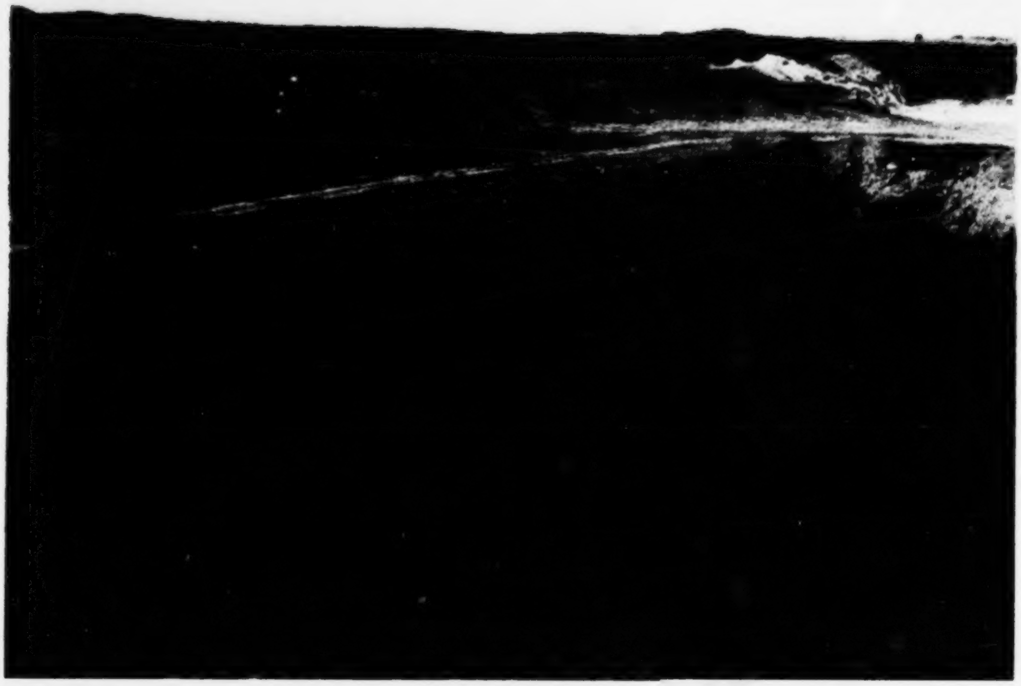


Plate 10

3.4.2 Surface mapping and sampling

The positions of the cracks were mapped as closely as possible and, although the ensuing map (Figure 31 and a larger scale version included in the rear flap of this report) did not include every minor crack, it gives a good general appreciation of the extent of fracturing.

In general, the cracks curve out from the pit wall at the east end of the pit and then tend to run parallel to the slope face before curving back towards the pit face to the west where they peter out.

Figure 32 shows four across sections chosen for study and analysis. Samples of the bentonitic clay band were taken for laboratory shear strength testing.

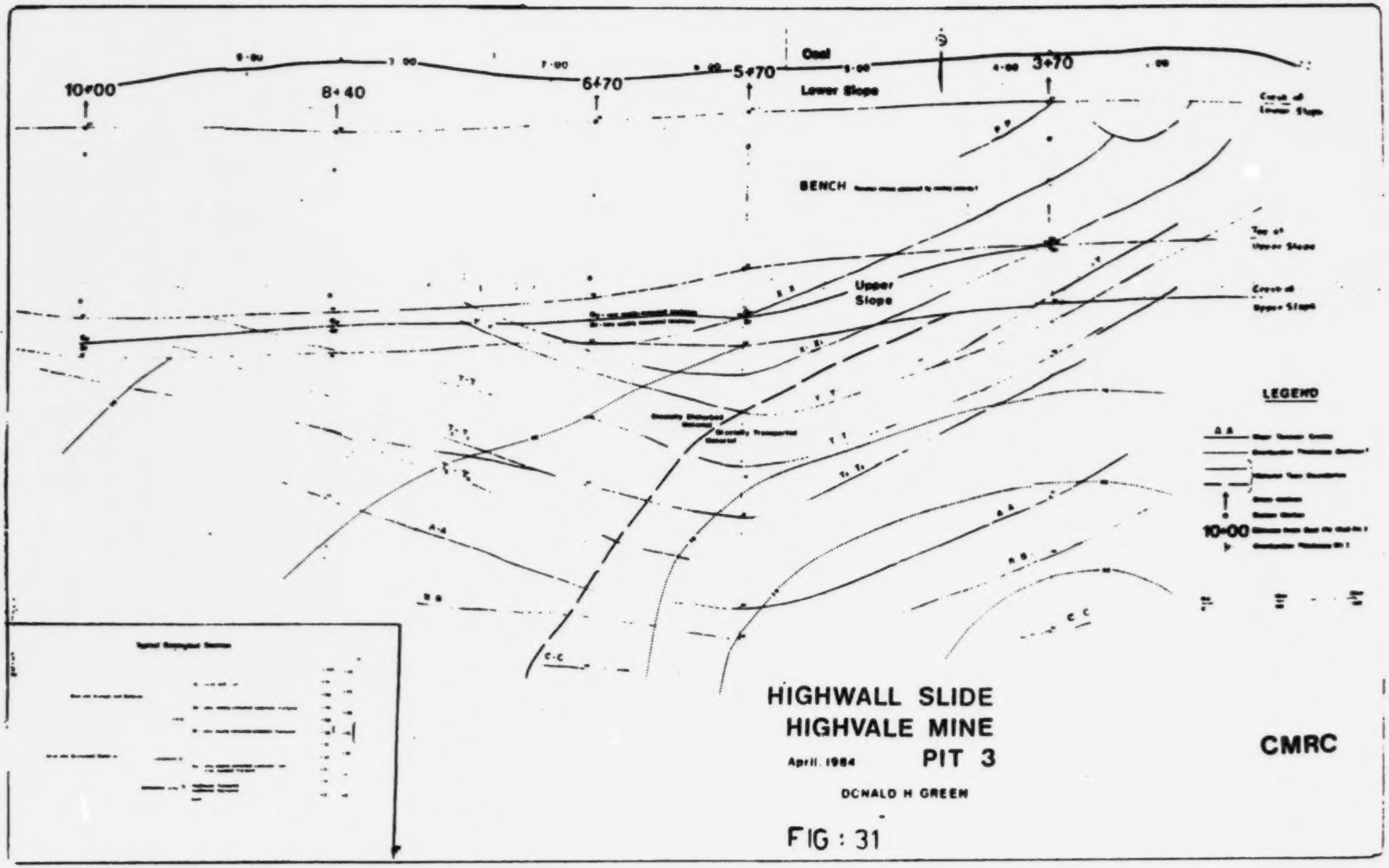
Field observations were also made of the attitude of the bentonitic clay band where it was accessible in the east end pit face. A frequency distribution curve for the true and apparent dip of this bentonitic clay band is derived in Appendix 1 from these measurements. From these results it was decided to use the value $\beta = -0.06^{\circ}$ with a standard deviation of 0.10° in the analyses.

3.4.3 Laboratory shear testing

The bentonitic clay samples were returned to the laboratory for shear testing. Appendix 3 gives a description of the sampling and testing methods together with the results from these tests. Appendix 2 describes the method used to determine the mean and standard deviations of the cohesion and angle of internal friction for this clay band. The results obtained by the tests carried out in 1983 by the consultant were also included in this analysis and are also given in Appendix 2. The following values were used for input into the analysis of multiple block plane shear slope failure carried out on this case history:-

$c = 9.3$ kPa standard deviation = 25.4 kPa

$\phi = 24.6^{\circ}$ standard deviation = 3.05°


Coal
Lower Slope
Crest of Lower Slope
BENCH
Top of Upper Slope
Upper Slope
Crest of Upper Slope
10+00
8+40
6+70
5+70
3+70
A-A
B-B
C-C
LEGEND
10+00

HIGHWALL SLIDE
HIGHVALE MINE
PIT 3
April 1984

DONALD H GREEN

CMRC

FIG : 31

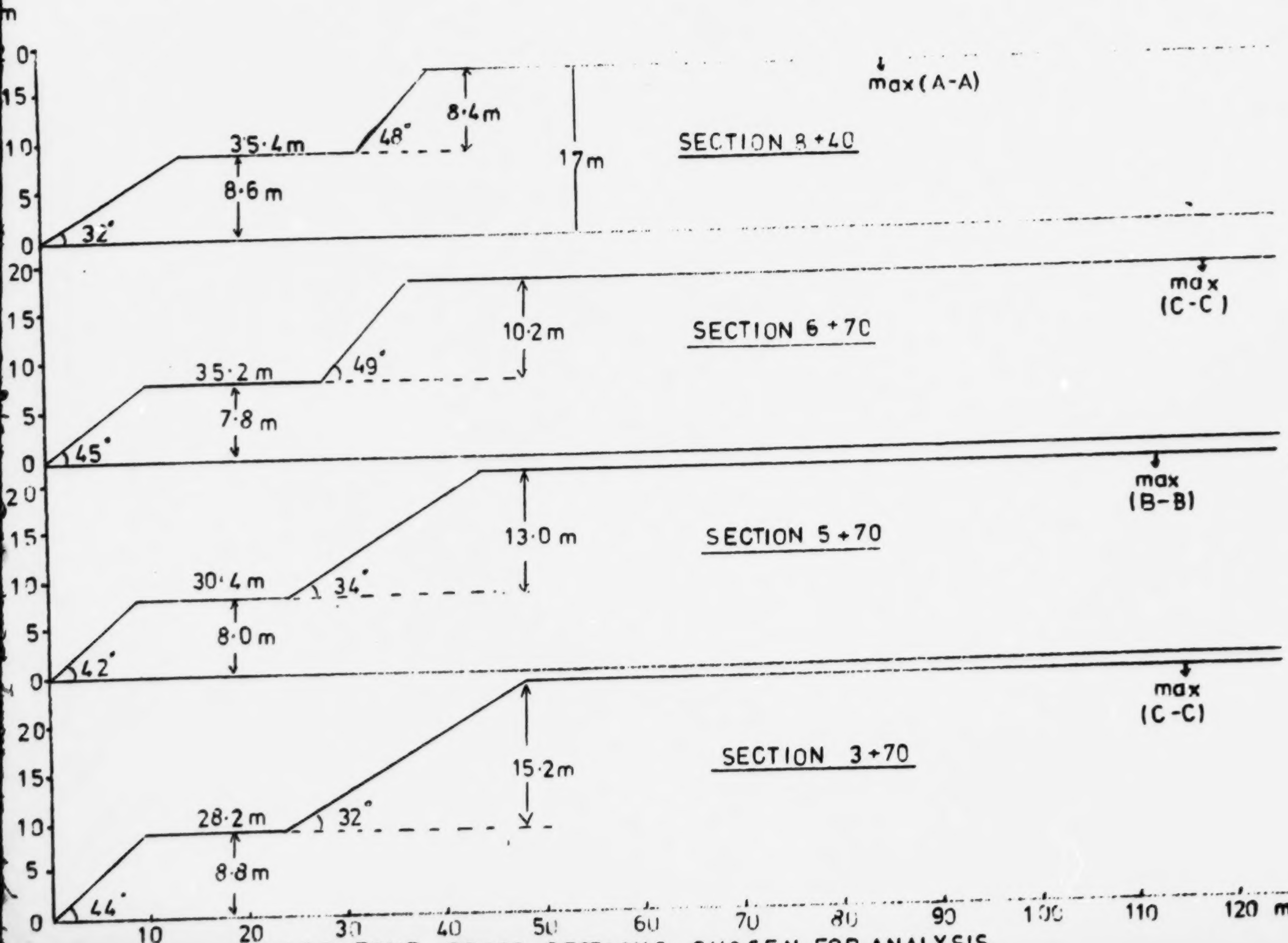

m
0
15
10
5
0
20
15
10
5
0
20
15
10
5
0
20
15
10
5
0
10
20
30
40
50
60
70
80
90
100
110
120 m
max (A-A)
SECTION 8 + 40
35·4m
48°
8·4m
17m
8·6 m
32°
max (C-C)
SECTION 6 + 70
35·2 m
49°
10·2 m
7·8 m
45°
max (B-B)
SECTION 5 + 70
30·4 m
34°
13·0 m
8·0 m
42°
max (C-C)
SECTION 3 + 70
28·2 m
32°
15·2m
8·8m
44°

FIG 3.2 : FOUR CROSS SECTIONS CHOSEN FOR ANALYSIS

3.4.4. Ground water information

Twenty piezometers were installed by the Alberta Research Council in September 1983 (11) as part of their on-going studies. Appendix 4 summarises the results obtained relative to the perched water table above the bentonitic band in the sandstone.

After consideration of these results and an estimation of the phraetic surface close to the pit (as discussed in Appendix 4) it was decided that a water table level of about 7-8 metres above the failure plane should be used in the pit slope analysis.

3.4.5 MBPSSF analysis

Appendix 5 gives a detailed reporting of the results of the MBPSSF analysis carried out together with a discussion of the results. The following summarises the results and conclusions from these analyses.

(1) It is clear from the analyses that the number of crack sets and their distance apart can vary widely with very little change in the input parameters. Thus the significance of a relatively large number of cracks occurring is not particularly relevant to the overall stability. This would explain the wide variation of crack set numbers and separations observed in the field.

(2) What is more important from the viewpoint of stability is the total extent of cracking. Figure 33 compares the maximum extent of cracking observed in the field on each of the face sections considered with the "mean maximum extent" of failure and the standard deviation of this value obtained from the probabalistic analyses for each section.

It is seen that these solutions bracket the field observations, although the standard deviations are large.

(3) For sections 3 + 70, 5 + 70 and 6 + 70 the line of mean maximum extent of cracking parallels the crack sets observed in the field. This is not

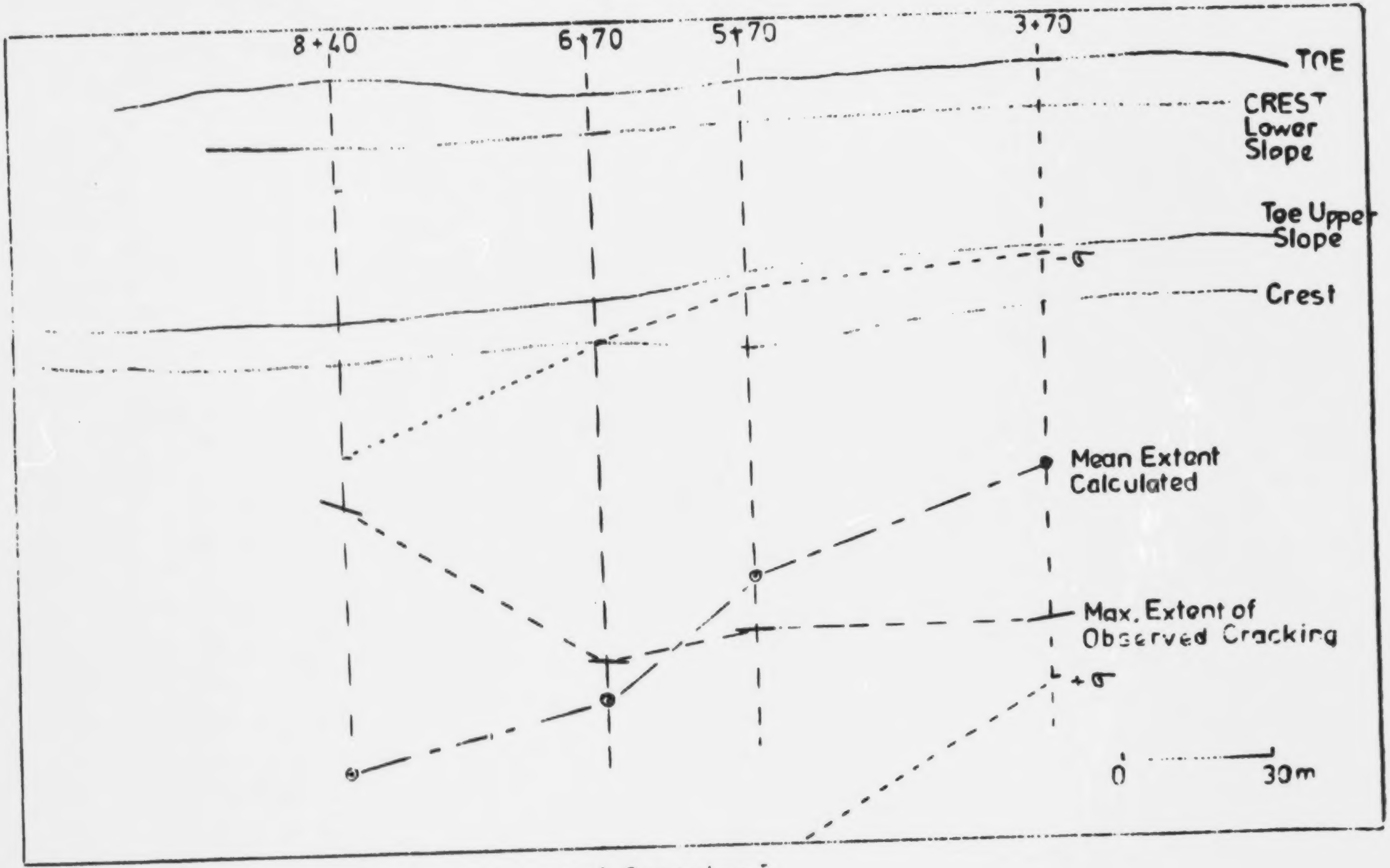

8+40
6+70
5+70
3+70
TOE
CREST
Lower
Slope
Toe Upper
Slope
Crest
-σ
Mean Extent
Calculated
Max. Extent of
Observed Cracking
+σ
0
30m

FIG 33 Observed and Calculated Extent of Cracking

the case for section 8 + 40 where theoretically the failure should extend even further back into the crest, whereas in this distance reduced. It is postulated that some change in lithology between sections 6 + 70 and 8 + 40 may have occurred. This should be investigated further should the opportunity arise.

(4) Overall the MBPSSF failure appears compatible with what is observed in the field.

3.4.6 Probability of failure extending beyond x_i metres ($H_W = 7.0$ m)

The probabalistic results for each section were then examined on the basis of the probability that failure would extend beyond any given distance, x_i metres, from the toe. Figure 35 shows the results of this evaluation.

It is seen that, for all sections, the probability of failure extending at least 30 metres from the toe is 100%. The probability that failure extends beyond 150 metres from the toe is much greater theoretically as the overburden depth decreases from section 3 + 70 ($\sim$20%, overburden 24 m) through to section 8 + 40 ($\sim$70%, overburden 17 m). This theoretical change is due to the increase of overburden increasing the frictional resisting force thus tending to stabilize the slope (or rather decreasing the instability). However, as noted in the previous section, the observed extent of cracking a section 8 + 40 is less than for the other cases. Possibly a lithological change has occurred.

3.4.7 Potential effect of drainage

The effect of lowering the water table, for section 5 + 70 only was then considered. Probabalistic solutions for different water table levels from $H_W = 1.5$ m to $H_W = 8$ m were carried out. Figure 34 shows the results. This figure clearly demonstrates the extreme sensitivity of the extent of failure to the variations in water table level. From these results Figure 36 was constructed. This figure shows the probability that failure will extend onto the dragline bench, completely across the bench and beyond the upper crest, plotted against water table level.

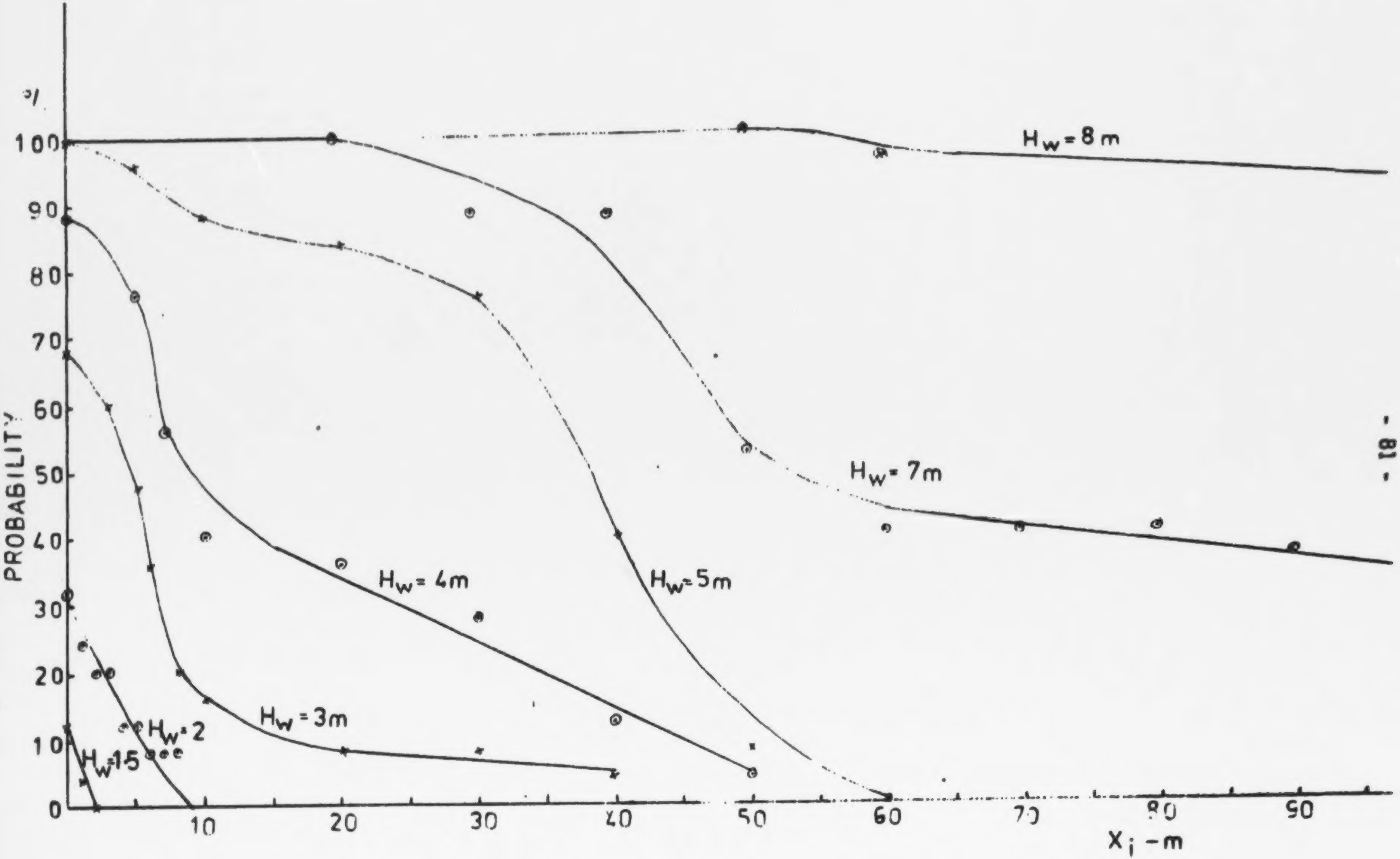


FIG 34 : PROBILITY OF CRACKING BEYOND X_i METRES - H_w VARIED - SECTION 5+70

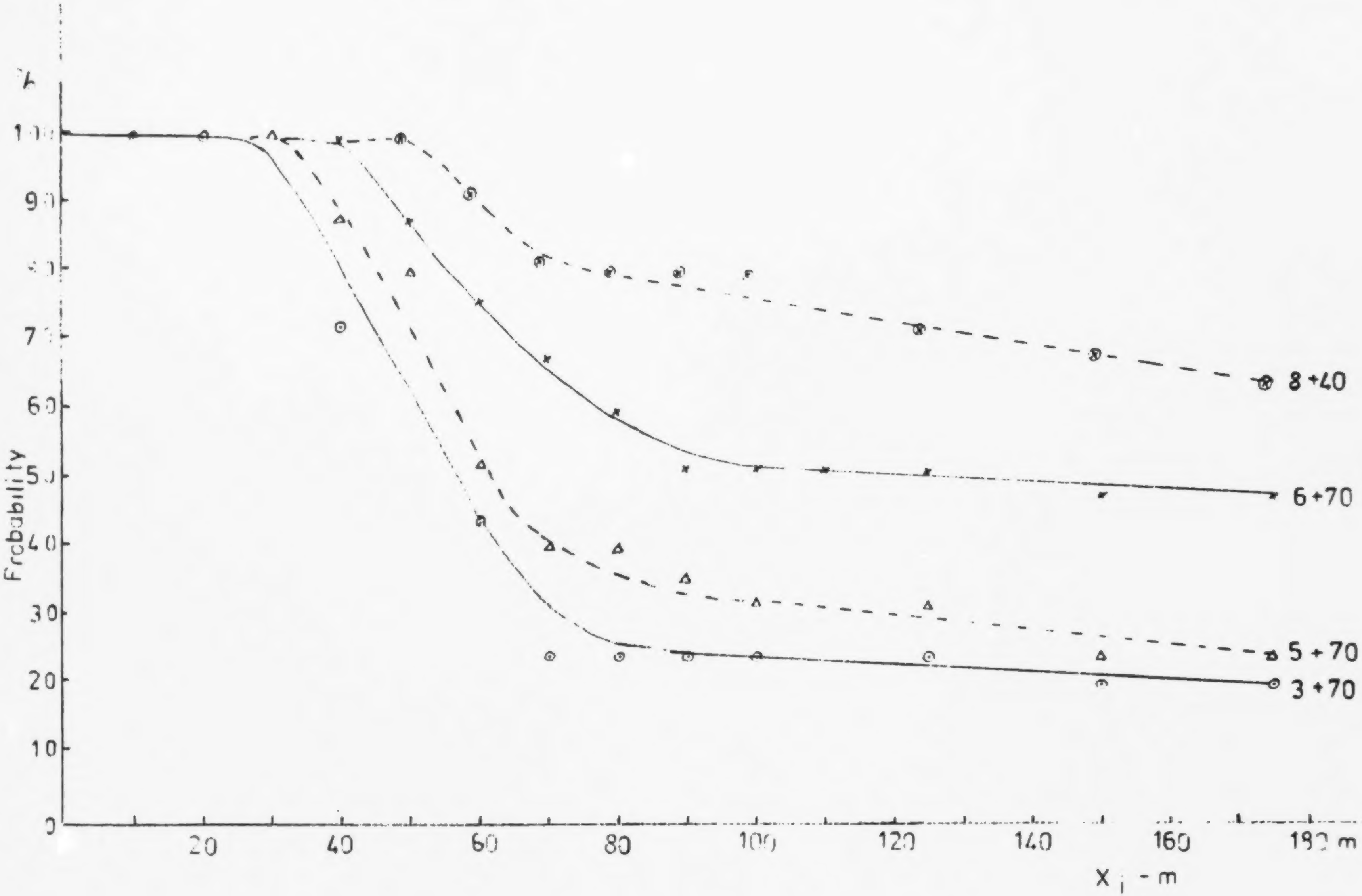


FIG 35 : PROBABILITY OF CRACKING EXTENDING BEYOND X_i METRES FROM THE TOE

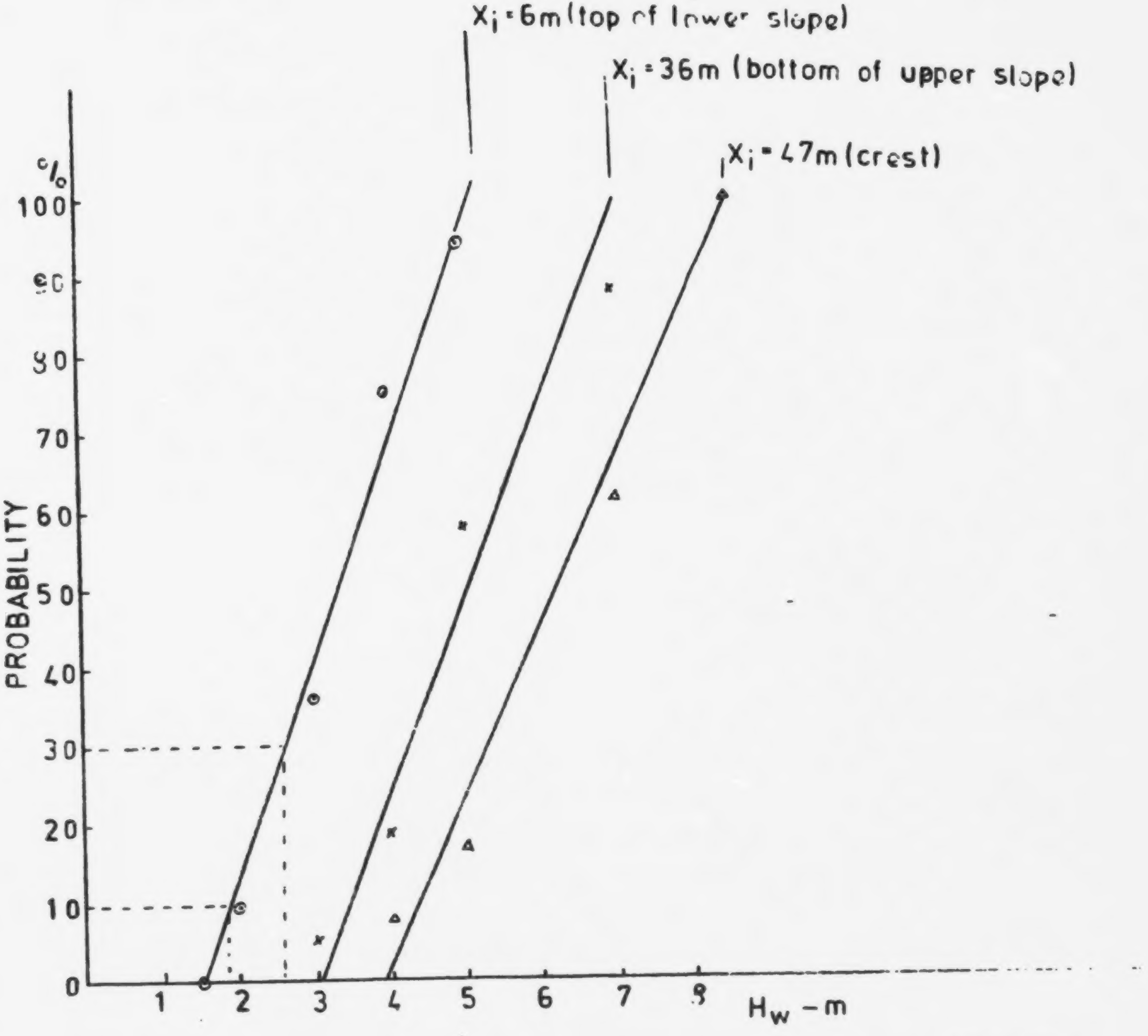


FIG 36 : PROBABILITY OF FAILURE EXTENDING BEYOND SPECIFIC DISTANCES VERSUS H_w - SECTION 5+70

Thus it is seen from this figure, that if the main design requirement is to prevent failure extending onto the dragline bench and hazard the dragline operations, then if the water table can be lowered to 2.5 m (from the current value of 7 m) then the probability of failure extending onto the dragline bench is reduced from 100% to 30%. If the water table can be lowered still further to 1.9 m, the probability reduces to 10%.

Recommendation. It is therefore recommended that the mine personnel endeavour to reduce the water table level as far as possible by drainage.

However, the evidence is that this overburden is not readily drainable (see Appendix 4). To drill horizontal holes from the face just above the failure plane would be expensive, since the holes would have to be exceptionally long, and the permeability of the overburden is low. This would be expensive with no guarantee of success.

It is suggested that a cheaper solution would be to drill vertical holes (much shorter than horizontal holes) through the overburden and into the coal seam. This would allow water to drain into the coal seam; the evidence in this area is that the coal is relatively permeable often acting as an aquifer. Consequently it would seem likely that any water drained from the overburden into the coal would readily seep away.

It is suggested that a trial of this method be carried out, by drilling a vertical hole to the coal seam and placing piezometers (in the overburden) just above the failure plane. In this manner the drawdown curve in the overburden could be obtained and the requisite hole spacing requirements be worked out to achieve the required water table level by the time mining takes place. There would appear to be no reason why vertical holes could not be drilled well in advance of mining (several years ahead) if the drainage proves, as suspected, to be very slow.

4. Conclusions

1. The four case histories studied can all be explained and analysed by assuming that the mode of failure is one of multiple block plane shear slope failure.
2. It is believed that this is the only mode of failure that would adequately explain the Highvale (1984) failure (case history #4)
3. Whether the failed zone is broken up into a large number of blocks (many tension cracks) or a relatively small number is dependent on small changes in the input parameters and would appear to be irrelevant to the overall slope stability problem.
4. More important is the total extent of the failure zone from the toe of the failure plane.
5. The total extent of the failure zone is exceptionally sensitive to the water table elevations. Relatively small changes in the water table level can have a very large affect on the probability of failure. Hence drainage, if possible, is the only satisfactory control method.
6. The analysis techniques developed allow the probability of failure extending beyond any specific distance from the toe to be assessed. Thus the required lowering of the water table to limit the extent of failure to a specified design probability can be calculated.

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6. Acknowledgements

The authors would like to thank Don Green and Steve Thornton for their valuable contributions in field mapping and sampling at the Highvale Mine.

APPENDIX 1

Derivation of normal distribution curve from histogram data

1. Theory

Let x be the mean value, let σ be the standard deviation, let n be the total number of measurements. Let Xmi be the class mean and d be the class width for the histogram, as illustrated in Figure A.1.1.

Let $$\lambda_i = \frac{X_{mi} - x}{\sigma}$$

Then if $\phi(\lambda i)$ is the nomalised density function, it is given by:-

$$\phi(\lambda i) = \frac{1}{\sqrt{2\pi}} \quad e^{-(\frac{\lambda^2}{\sqrt{2}})}$$

and the relative frequency distribution, q_i, is given by:-

$$qi = \frac{d}{\sigma} \quad \phi(\lambda i)$$

and the absolute frequency, k_i, Is given by:-

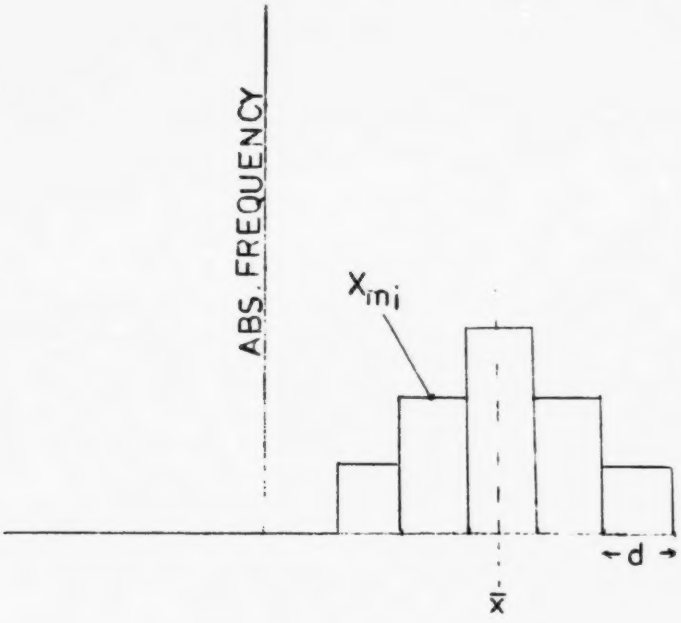
$$k_i = n\, q_i$$

Let $Q(\lambda i)$ be the distribution function

i.e. $Q(\lambda i)$ is the probability that a value is > Xmi, then

$$\phi(\lambda i) = \frac{1}{\sqrt{2\pi}} \int_{\lambda}^{\infty} e^{-(\frac{t^2}{2})} \, dt$$

Now a polynomial approximation can be used to compute $Q(\lambda i)$ for a given


ABS. FREQUENCY
X_{mi}
d
$\bar{x}$

n = Number measurements

$\bar{x}$ = Mean

σ = Standard deviation

X_{mi} = Class mean

d = Class width

FIG A1.1 : NOMENCLATURE

Xmi:-

Define

$$R = Q(\lambda_i)\ (b_1 t + b_2 t^2 + b_3 t^3 + b_4 t^4 + b_5 t^5) + E(\lambda)$$

where $E(\lambda) < 7.5 \times 10^{-8}$

and $t = \frac{1}{1 + r|\lambda|}$

where $r = 0.2316419$
$b_1 = 0.319381530$
$b_2 = -0.356563782$
$b_3 = 1.781477937$
$b_4 = -1.821255978$
$b_5 = 1.330274429$

$y(\lambda_i) > 0$ then $Q(\lambda_i) = R$

or $y(\lambda_i) < 0$ then $Q(\lambda_i) = (1-R)$

A hand calculator was programmed to determine λ_i, $\phi(\lambda_i)$, q_i, k_i and $Q(\lambda_i)$ for any specified Xmi value given $\bar{x}$, σ, d and n.

2. Application to the frequency distribution of the true and apparent dip of the bentonitic clay layer in pit 03 at Highvale Mine.

Table A1 shows the true dip and strike of this clay layer as measured in the pit and gives the calculated apparent dip angles for the east wall and south wall respectively.

Table A2 gives the histogram frequency data obtained from these measurements, the normal frequency distribution curve calculated from the mean and standard deviation. The probability that any value is greater than the class mean Xmi is also given.

Figure A.1.2 shows the absolute frequency distribution for the true dip data and Figure A.1.3 gives the probability that a given value of true dip is greater than Xim.

Figure A.1.4 and A.1.5 give the histograms and determined absolute frequency distribution curves for the apparent dip in the east wall and south wall respectively.

TABLE A1: DIP OF BENTONITIC CLAY BAND - PIT 03 - HIGHVALE

Observation #	True Dip 8°	Dip Direction (Corrected to True N)	Strike	Calculated Apparent Dip	
				East Wall	South Wall
1	- 0.4°	316.5	46.5	-0.27	-0.29
2	0	-	-	0	0
3	-0.25°	312.5	42.5	-0.18	-0.17
4	0	-	-	0	0
5	0	-	-	0	0
6	0	-	-	0	0
7	0	-	-	0	0
8	0	-	-	0	0
9	0	-	-	0	0
10	-0.4°	297.5	27.5	-0.35	-0.18
11	-0.3°	293.5	23.5	-0.28	-0.12
12	+0.2°	305.5	35.5	+0.16	+0.12
13	-0.3°	291.5	21.5	-0.28	-0.11
14	0	-	-	0	0
15	0	-	-	0	0
16	-0.3°	311.5	41.5	-0.23	-0.20
17	-1.0°	283.5	13.5	-0.97	-0.23
18	-0.2°	300.5	30.5	-0.17	-0.10
19	-0.2°	302.5	32.5	-0.17	-0.11
20	0°	-	-	0	0
21	0°	-	-	0	0
22	+0.2°	282.5	12.5	+0.19	+0.05
23	-0.2°	293.5	23.5	-0.18	-0.08
24	0°	-	-	0	0
MEAN	-0.13°	299.3	29.3	-0.11	-0.06
S.D.	0.25°	11.0	11.0	0.23	0.10
n	24	12	12	24	24

TABLE A2: HISTOGRAM FREQUENCY DATA

TRUE DIP: $\bar{x} = -0.13$, $\sigma = 0.25$, $n = 24$, choose $d = 0.4$

Class mean Xim	Abs frequency	Calculated frequency distribution	% Probability that value >Xim
-0.8	1	0.42	99.6
-0.4	8	8.5	86.0
0	13	13.4	30.2
+0.4	2	1.6	1.7
+0.8	0	0.015	0.01

APPARENT DIP - EAST WALL $\bar{x} = -0.11$, $\sigma = 0.23$, $n = 24$, choose $d = 0.2$

-1.0	1	.005	99.99
-0.8	0	.09	99.9
-0.6	0	.86	98.3
-0.4	1	3.8	89.6
-0.2	8	7.7	65.2
0	12	7.4	31.7
0.2	2	3.4	8.9
0.4	0	0.7	1.3
0.6	0	0.7	0.1

APPARENT DIP - SOUTH WALL $\bar{x} = -0.06$, $\sigma = 0.10$, $n = 24$, choose $d = 0.2$

-1.0	0	0	100
-0.8	0	0	100
-0.6	0	0	100
-0.4	0	0.05	99.9
-0.2	8	7.2	91.9
0	15	16.0	27.5
0.2	1	65	0.46
0.4	0	0	0
0.6	0	0	0

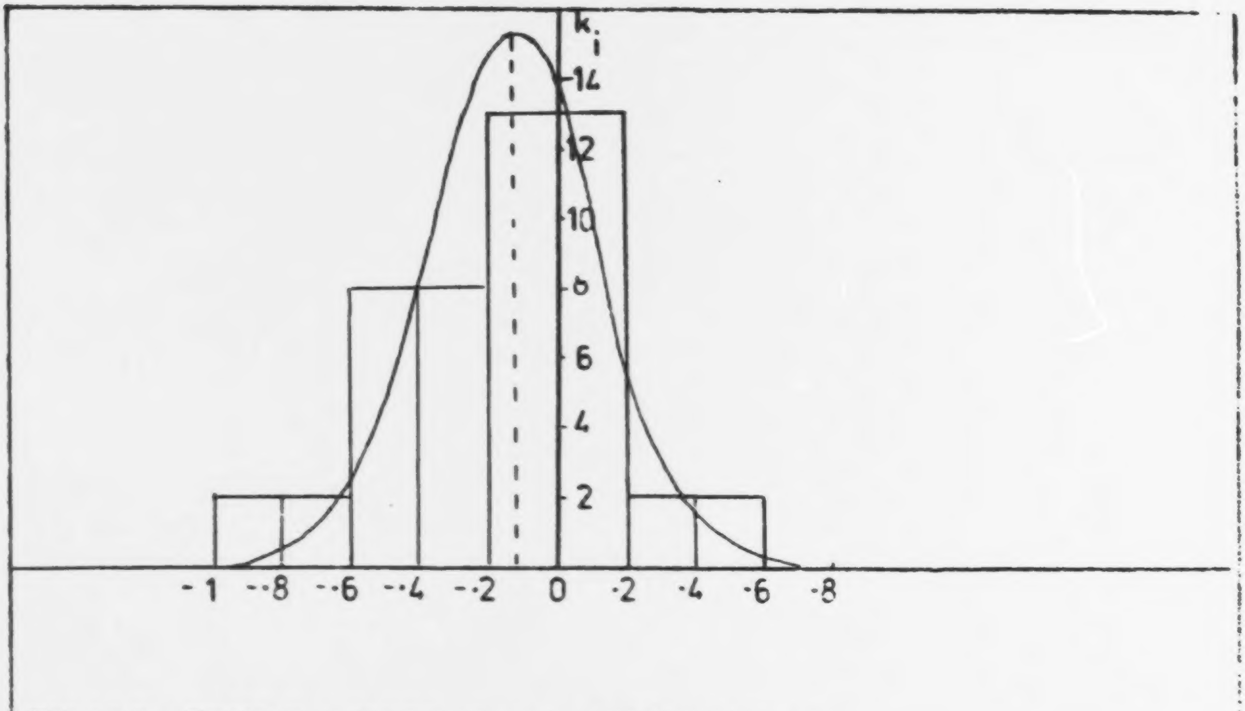


FIG A1·2 : TRUE DIP FREQUENCY DISTRIBUTION

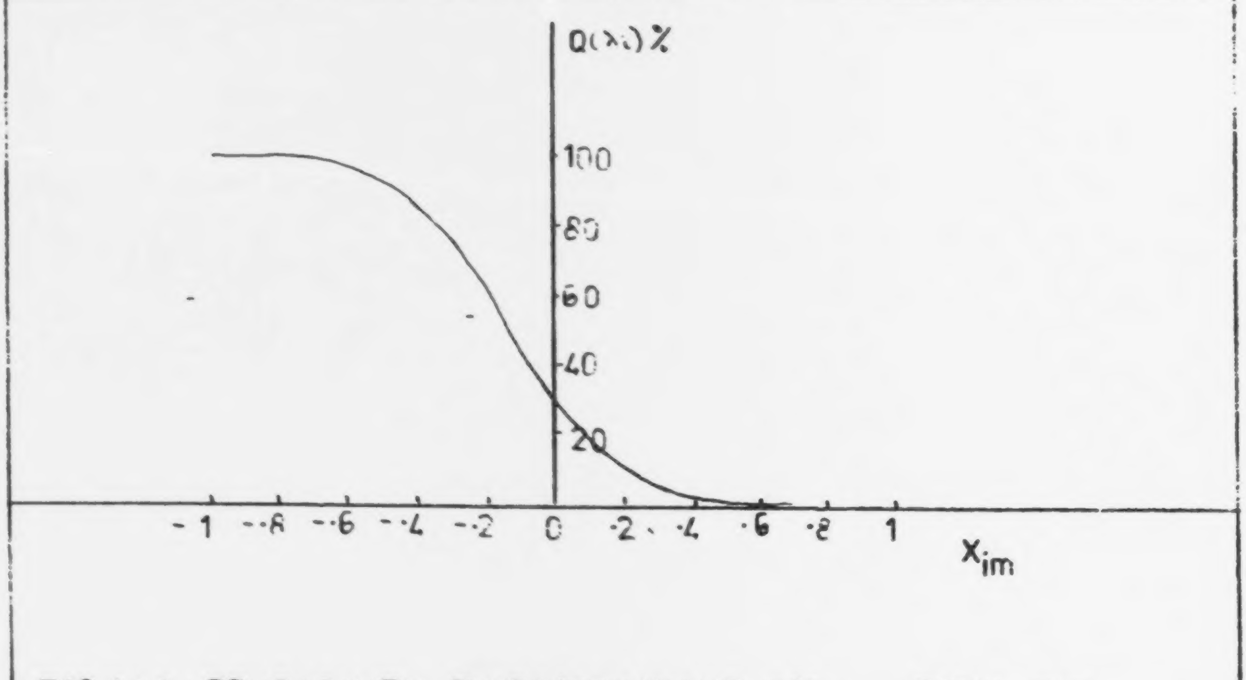


FIG A1·3 : PROBABILITY THAT GIVEN VALUE $>X_{im}$ -TRUE DIP

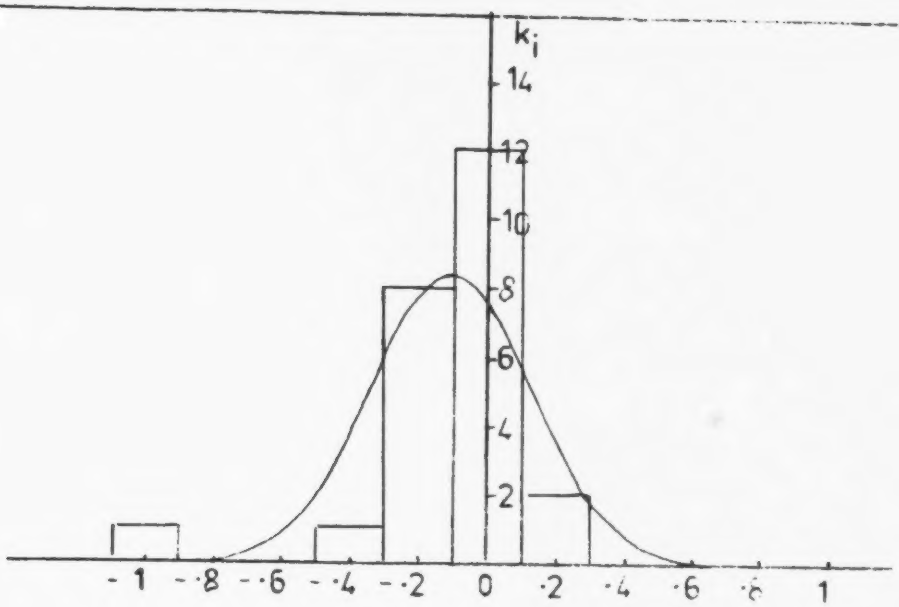


FIG A1·4 : APPARENT DIP - EAST WALL

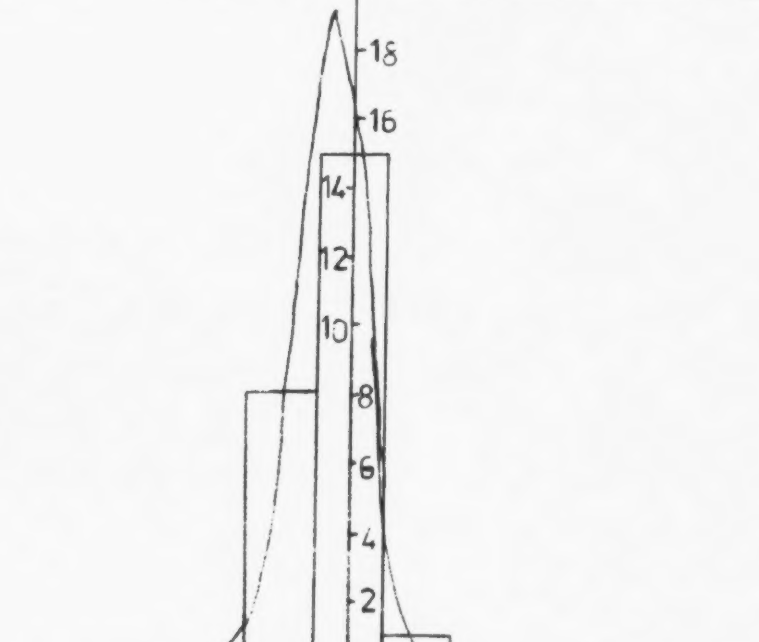


FIG A1·5 : APPARENT DIP - SOUTH WALL

APPENDIX 2

Determination of the frequency distribution of the cohesion and angle of friction

1. The Problem

The cohesion c is the intercept on the shear stress axis, and the angle of friction, ϕ, is the slope of the shear stress versus normal stress curve. Consequently, these are not directly measured parameters but are secondary derived parameters from the shear/normal stress relationship. The tests are normally conducted over a range of τ and σ values and, usually a linear relationship is assumed, as follows:-

$$\tau = (\mu \pm \alpha)\sigma + (c \pm \alpha_c) \quad (1)$$

where τ is the shear stress, σ is the normal stress, $\mu = \tan^{-1}\phi$ where ϕ is the angle of friction and c is the cohesion.

Let α be the standard error of μ and αc be the standard error of c. Given n measurements of τ and σ, assuming this linear relationship, the best fit straight line can be obtained by the least squares regression analysis together with the standard errors of the coefficients.

Let $\tau = y$ and $\sigma = x$, then $\tau = (\mu \pm \alpha)\, x + (c \pm \alpha c)$ (2)

then, from regression analysis, we have:-

$$\mu = \frac{\left(n\,\Sigma\, xy - \Sigma x \Sigma y\right)}{\left(n\,\Sigma\, x^2 - (\Sigma x)^2\right)} \quad (3)$$

$$c = \frac{\left(\Sigma y - \mu\, \Sigma x\right)}{n} \quad (4)$$

The correlation coefficient r is given by:-

$$r = \frac{\left(n\,\Sigma\, xy - \Sigma x \Sigma y\right)}{\left\{\left[n\,\Sigma x^2 - (\Sigma x)^2\right]\left[n\,\Sigma y^2 - (\Sigma y)^2\right]\right\}^{1/2}} \quad (5)$$

and the standard errors of the coefficients are given by:-

$$\alpha^2 = \frac{n}{(n-2)} \left[\frac{\left\{ \Sigma\ (y - \mu x - c)^2 \right\}}{\left\{ n\ \Sigma x^2 - (\Sigma x)^2 \right\}} \right]$$

and $$\alpha_c^2 = \frac{\alpha^2}{n} \quad (\Sigma x^2)$$

Hence, given the n data sets the coefficients c and μ can be calculated together with their standard errors α_c and α.

Now if σ = standard deviation of μ and σ_c is the standard deviation of c, they are related by:-

$$\sigma = \alpha n^{1/2}$$
$$\sigma_c = \alpha_c n^{1/2}$$

2. Correction for small data sets

When the number of data sets, n, is small the standard deviation determined from the above is underestimated. It is appropriate to use Bessel's correction factor to produce a better estimate of the standard deviations. Let σ^1 and $\sigma_c{}^1$ be the "corrected" standard deviations, then Bessel's correction gives:-

$$(\sigma^1)^2 = \frac{n}{(n-1)} (\sigma)^2$$

and

$$(\sigma_c{}^1)^2 = \frac{n}{(n-1)} (\sigma_c)^2$$

A program was written for a hand held calculator allowing the input of n data sets (τ i, σ i) and the calculation of

$$\mu,\ c,\ r,\ \alpha,\ \sigma,\ \sigma^1,\ \alpha_c,\ \sigma_c \text{ and } \sigma_c{}^1$$

This was used in processing the data given in section 4 below.

3. Determination of the absolute frequency distribution curve for c and μ

Having determined the mean value and corrected standard deviation of μ (or c) using the method given above, then the frequency distribution curve for μ (or c) can be derived by the method given in Appendix 1, making use of the polynomial approximation.

4. Application to determination of c and ϕ distributions for the bentonitic clay band at Highvale Mine.

4.1 Data set 1

Table A3 and Figure A.2.1 give the results of direct shear tests carried out in 1983 (10) for the peak and residual stresses at failure. This table also gives the results of the calculations by the method given above for the determination of the frequency distribution for c and ϕ from this data.

From this analysis the following values are used for the input data for the Highvale (1983) case history given in the main text (peak stress data).

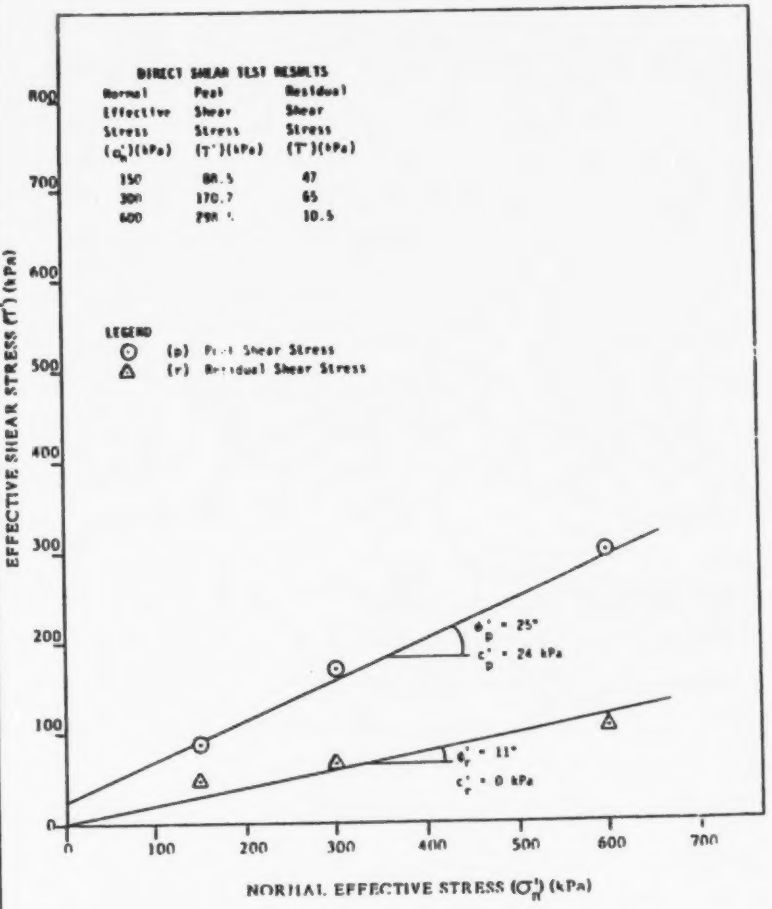
c = 24.6 kPa s.d. = $_{\sigma}c^{1}$ = 25.6 kPa
and $\phi = \tan^{-1} 0.461 = 24.7^{\circ}$ s.d. = 3.05°

4.2 Data set 2

The authors collected samples from the bentonitic clay band immediately above the coal seam at Highvale mine in 1984. The shear test results on these samples are given in Appendix 3. Table A4 summarises the results of these tests and gives the peak and residual values of c and ϕ determined from these tests, together with their standard deviation.

4.3 Data set 3

The authors also collected samples from a clay band near the coal contact at Highvale Mine in 1984. The shear test results are given in Appendix 3 and are summarized in Table A5 together with the peak c and ϕ values and their standard deviations.



DIRECT SHEAR TEST RESULTS

Normal Effective Stress (σ_n')(kPa)	Peak Shear Stress (τ')(kPa)	Residual Shear Stress (τ')(kPa)
150	88.5	47
300	170.7	65
600	298.[illegible]	10.5

FIG. A 2·1	Highvale Mine Pit 03, Cut 07 Highwall Failure Study	Effective Stress Mohr Envelope for Bentonitic Clay (Soil # 4) Hole No. HV-83-406 Sample No. U-10(14.7m to 14.9m)

TABLE A3: SHEAR TEST RESULTS - DATA SET 1

Normal effective stress $\sigma_n{}^1$ (kPa)	Peak shear stress τ^1 (kPa)	Residual shear stress $\tau_r{}^1$(kPa)
150	88.5	47
300	170.7	65
600	298.5	100.5*

Calculation results

c	24.6 kPa	29.3 kPa
α_c	11.98	0.164
σ_c	20.75	0.28
$\sigma_c{}^1$	25.41	0.35
μ	0.461	0.119
α	0.030	0.0004
σ	0.052	0.0007
σ^1	0.064	0.0009
Corr. coeff	0.998	1.0

*NOTE: Figure A.2.1 reproduced from reference 1 has a typographic error; residual shear stress at 600 kPa should be 100.5 kPa.

NOTE: In the original work (10) the residual cohesion was "forced fitted" to 0 kPa. The regression analysis shows that this is not the best data fit. This changes the angles of friction from

	Original to	Regression analysis
Peak ϕ	25°	$\tan^{-1} 0.461 = 24.7^\circ \pm 1.4^\circ$
Residual ϕ	11°	$\tan^{-1} 0.119 = 6.8^\circ \pm 0.02^\circ$

TABLE A4: SHEAR TEST RESULTS - DATA SET 2

	Normal effective stress σ_n^1 kPa	Peak shear stress τ^1 (kPa)	Residual shear stress τ_r^1 (kPa)
1.	193.7	89.1	84.0
2.	369.5	154.2	149.2
3.	36.5	15.2	11.2
	c	2.91	-1.20
	α_c	6.93	6.41
	σ_c	12.01	11.10
	σ_c^1	14.71	13.59
	μ	0.417	0.414
	α	0.029	0.026
	σ	0.050	0.046
	σ^1	0.061	0.056
Corr. coeff. r.		0.998	0.998

Angle of friction peak = $\tan^{-1} 0.417 = 22.6^\circ \pm 1.4^\circ$
residual = $\tan^{-1} 0.414 = 22.5^\circ \pm 1.3^\circ$

NOTE: Re-residual values; once the peak stress was exceeded the shear force was quite variable, it would appear that these past peak values did not reach the true residual value.

TABLE A5: SHEAR TEST RESULTS - DATA SET 3

	Normal effective stress σn^1 kPa	Peak shear stress τ^1 (kPa)	Residual shear stress $\tau_r{}^1$ (kPa)
1.	193.7	105.8	79.6
2.	36.5	35.8	?
3.	364.0	151.6	?
	c	27.9	
	α_c	12.1	
	σ_c	21.0	
	$\sigma_c{}^1$	25.7	
	μ	0.35	
	α	0.05	
	σ	0.09	
	σ^1	0.11	
Corr. coeff. r.		0.989	

Angle of friction = $\tan^{-1} 0.35 = 19.4^{\circ} \pm 2.6^{\circ}$

4.4 Compilation of all data sets

The data from all the above tests have been lumped together and the c and ϕ values for peak and residual stresses, with their deviations, have been determined in Table A6.

Figure A.2.2 shows this data plotted on a shear/normal stress curve and Figures A.2.3 and A.2.4 shows the distribution curves for the peak cohesion and peak friction angles respectively.

From this analysis the following values are used for the input data for the Highvale (1984) case history given in the main text:-

$c = 9.3$ kPa	s.d. = 25.4 kPa
$\phi = 24.6^{\circ}$	s.d = 3.05

TABLE A6: SHEAR TEST RESULTS - ALL DATA

Normal effective stress σ_n^1 kPa	Peak shear stress τ^1 (kPa)	Residual shear stress τ_r^1 (kPa)
150	88.5	47
300	170.7	65
600	298.5	100.5
193.7	89.1	84.0
369.5	154.2	149.2
36.5	15.2	11.2
193.7	105.8	79.6
36.5	35.8	-
36.4	151.6	-
c	9.29	33.4
α_c	11.0	23.9
σ_c	33.1	63.1
σ_c^1	35.1	68.2
μ	0.457	0.164
α	0.037	0.074
σ	0.110	0.202
σ^1	0.116	0.218
r	0.978	0.693

peak = $\tan^{-1} 0.457 = 24.6^\circ \pm 1.8^\circ$

residual = $\tan^{-1} 0.164 = 9.3^\circ \pm 4.3^\circ$

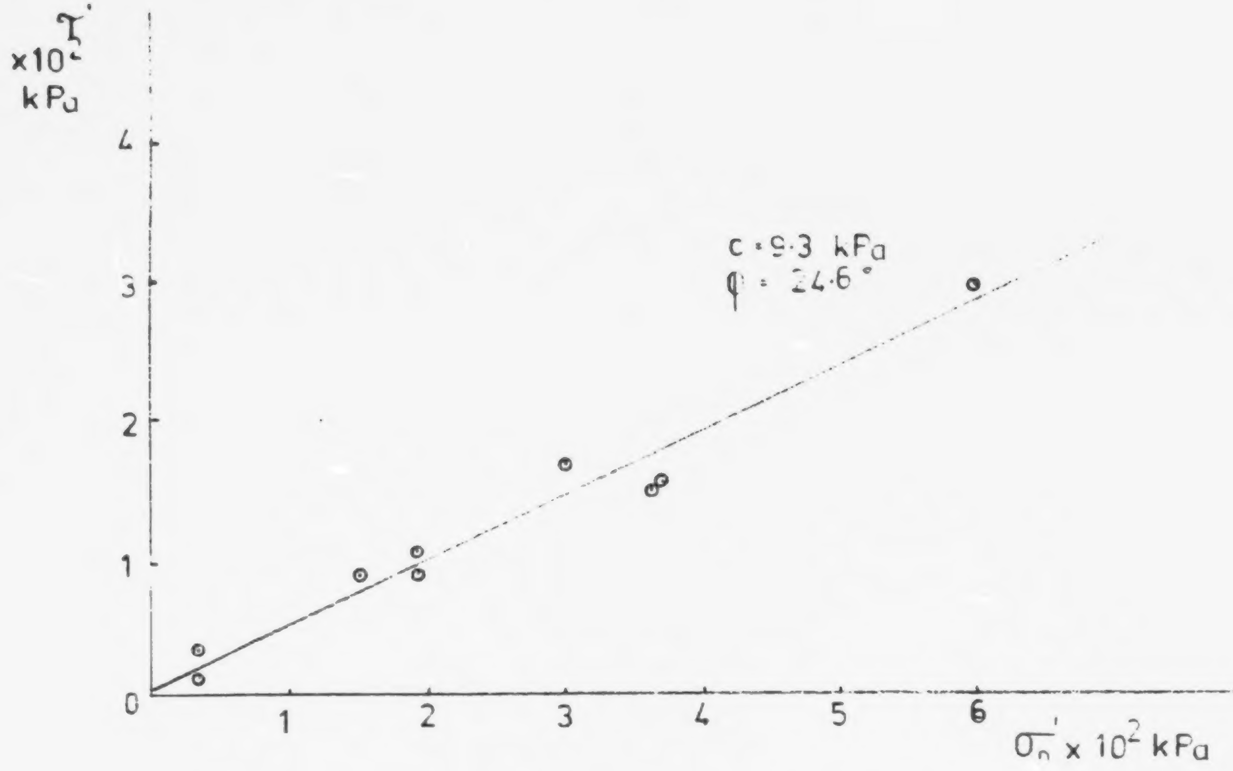


FIG A 2.2 :SHEAR TEST RESULTS - ALL DATA

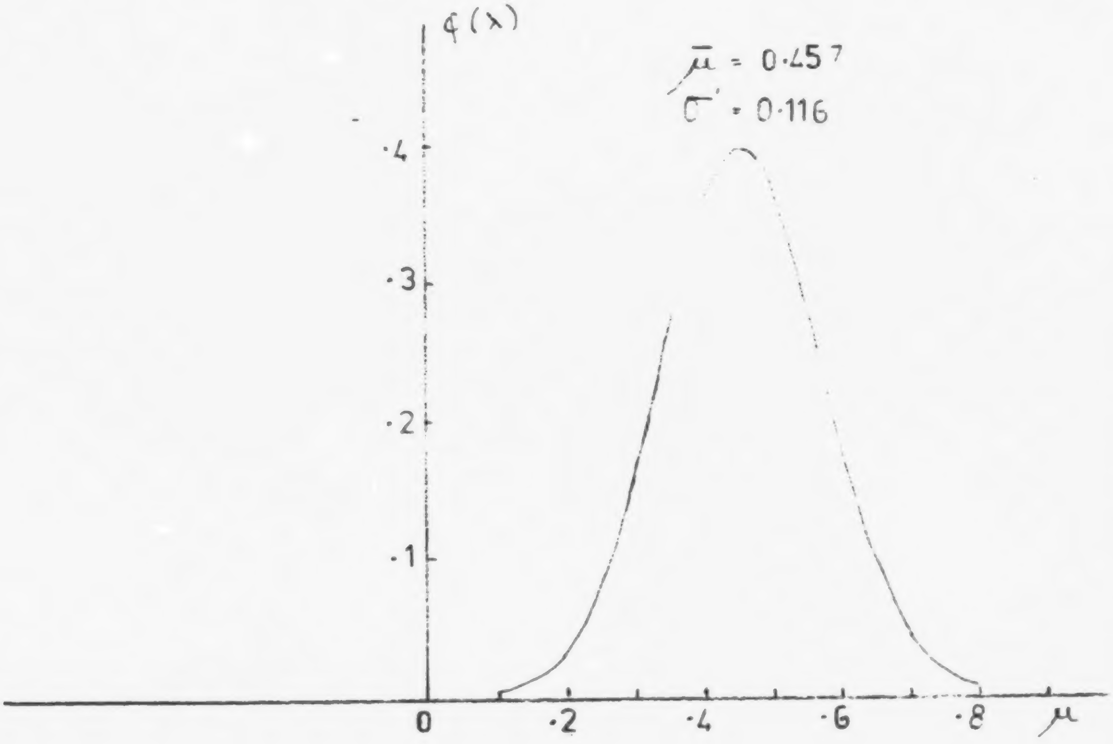


FIG A 2·3 : DISTRIBUTION CURVE FOR μ - ALL DATA - PEAK

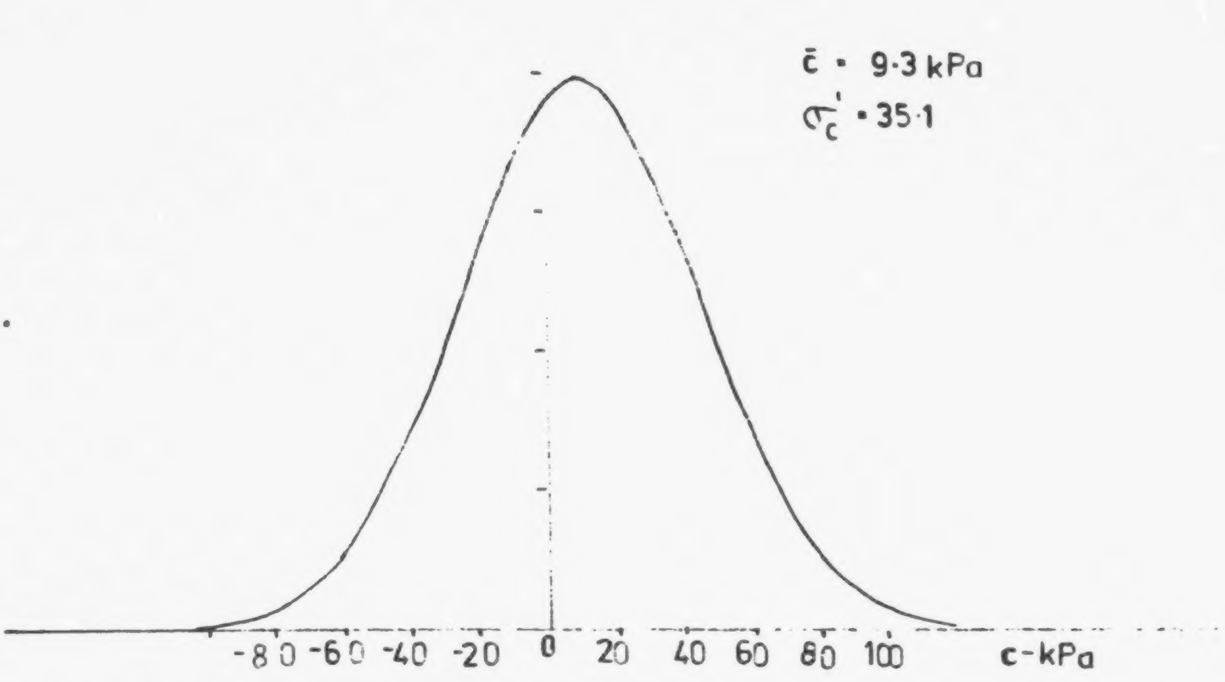


FIG A2·4: DISTRIBUTION CURVE FOR c - ALL DATA - PEAK

The objective of collecting the clay/coal contact from Site #2 was to measure the drained shear strength along the contact, but the coal was too friable and fragile to hold together during transportation and preparation. Consequently, these tests assess the shear strength in the clay within 5-10 mm of the contact.

Results

Basic data from the tests are tabulated in Tables A7, A8 and A9 and the shear strength envelopes are shown in Figs. A31, A32 and A33.

TABLE A7
CLAY SAMPLE FROM SITE #1 - PEAK STRENGTHS, BULK DENSITIES AND MOISTURE CONTENTS

Sample	Bulk density MN/cu.m	Moisture content (before test) %	Moisture content (after test) %	Effective normal stress kPa	Peak strength kPa
1	12446	31.8 39.8	39.8	36.5	15.2
2	14693	35.3 35.0	35.0	193.8	88.9
3	15306	38.1 36.9	32.3	369.6	154.4

TABLE A8
CLAY SAMPLE FROM SITE #2 - PEAK STRENGTHS, BULK DENSITIES AND MOISTURE CONTENTS

Sample	Bulk density	Moisture content (before test)	Moisture content (after test)	Effective normal stress	Peak strength
	MN/cu.m	%	%	kPa	
1	15998	27.2 31.3	58.0	36.5	35.9
2	15369	43.2 32.6	35.2	193.8	105.5
3	15290	36.2 24.9	42.3	364.1	151.7

TABLE A9
CLAY SAMPLE FROM SITE #1 - RESIDUAL STRENGTHS, BULK DENSITIES AND MOISTURE CONTENTS

Sample	Bulk density	Moisture content (before test)	Moisture content (after test)	Effective normal stress	Peak strength
	MN/cu.m	%	%	kPa	
1	15950	57.8 53.4		36.5	22.1
2	(As for sample 1)			64.1	30.3
3	(As for sample 4)			189.6	57.2
4	16343	58.0 52.8		364.1	96.5

FIG A3·1 PEAK STRENGTHS ON CLAY SEAM SITE 1

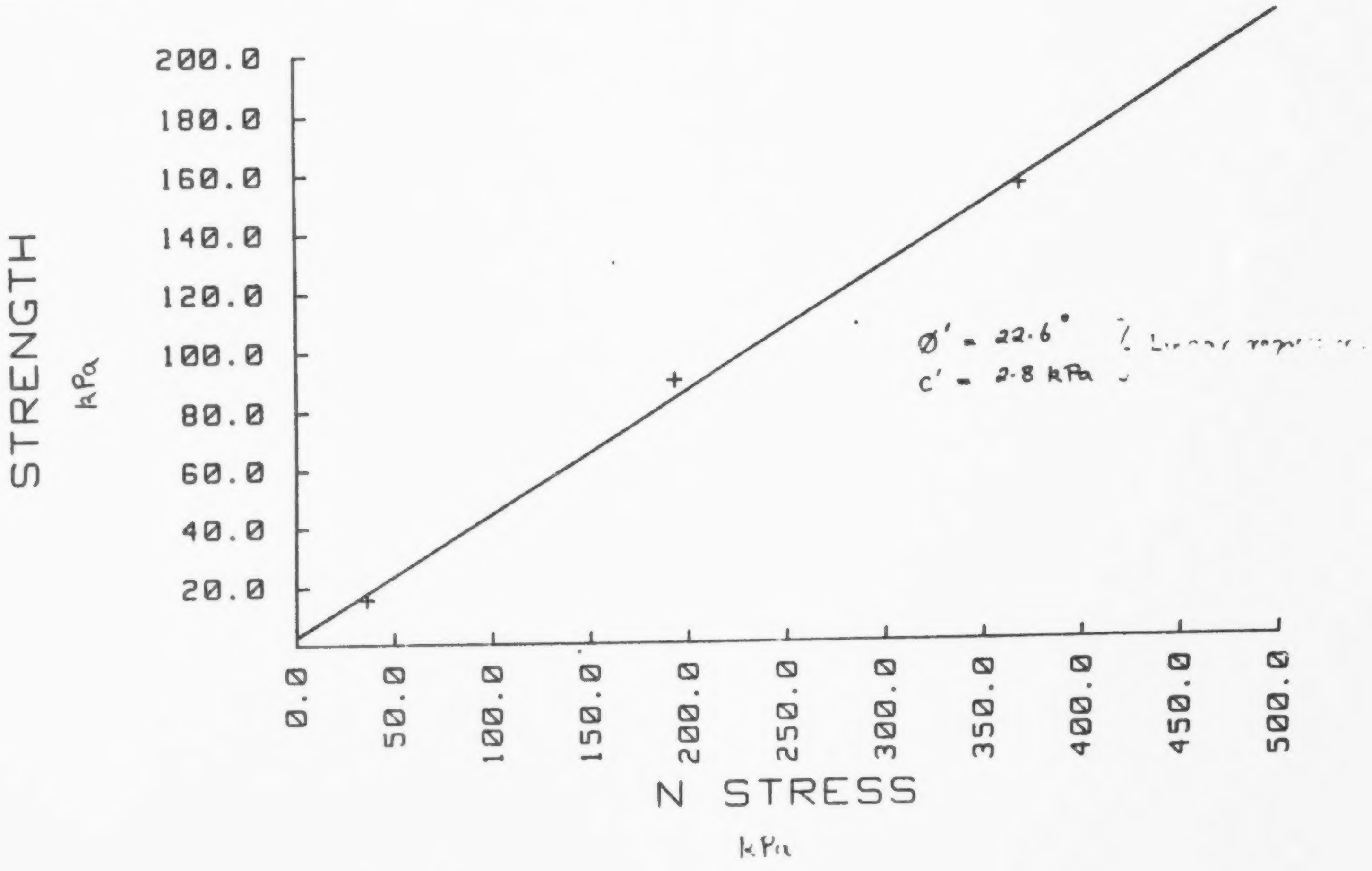
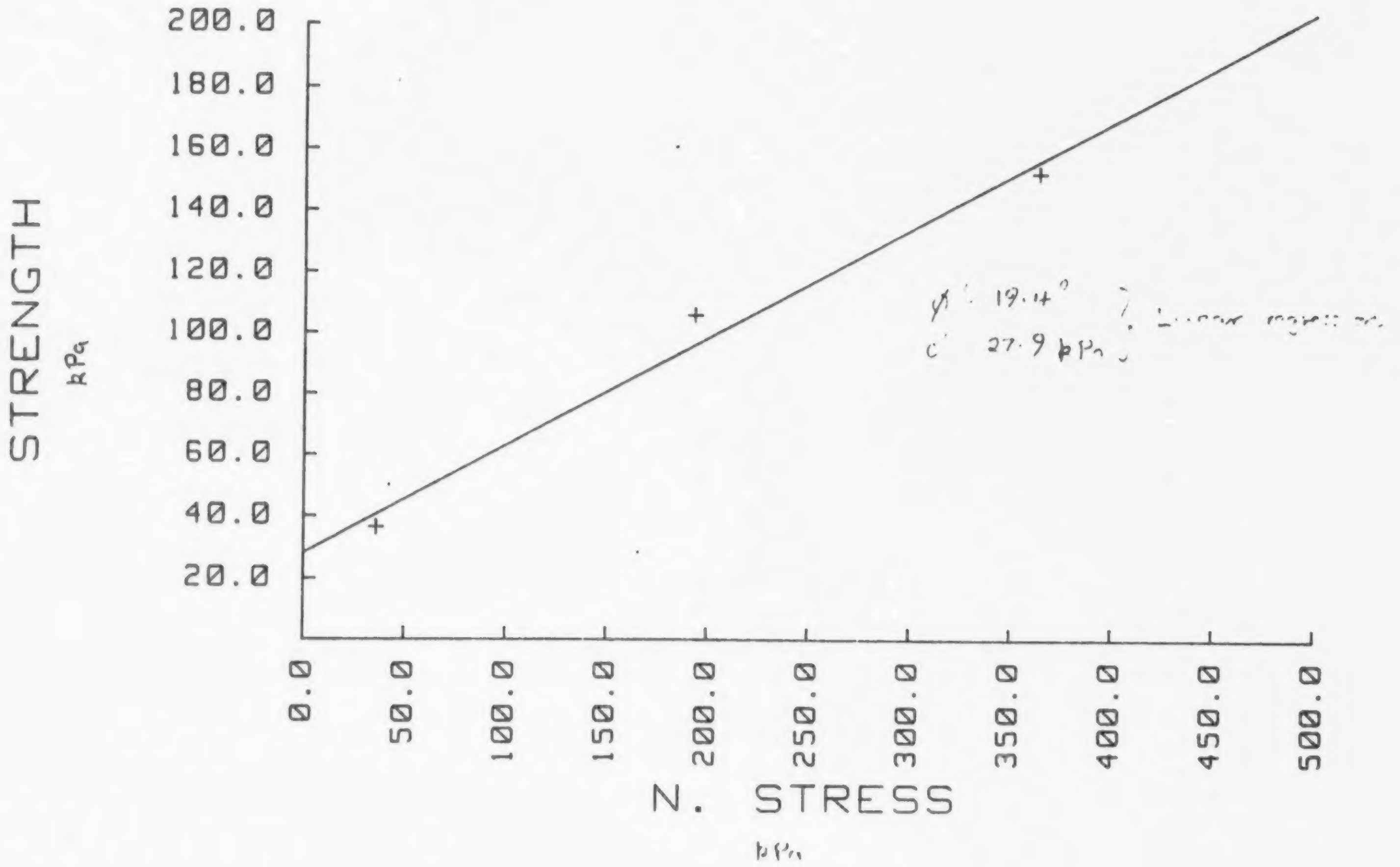


FIG A3·2 PEAK STRENGTHS ON CLAY NEAR COAL CONTACT SITE,



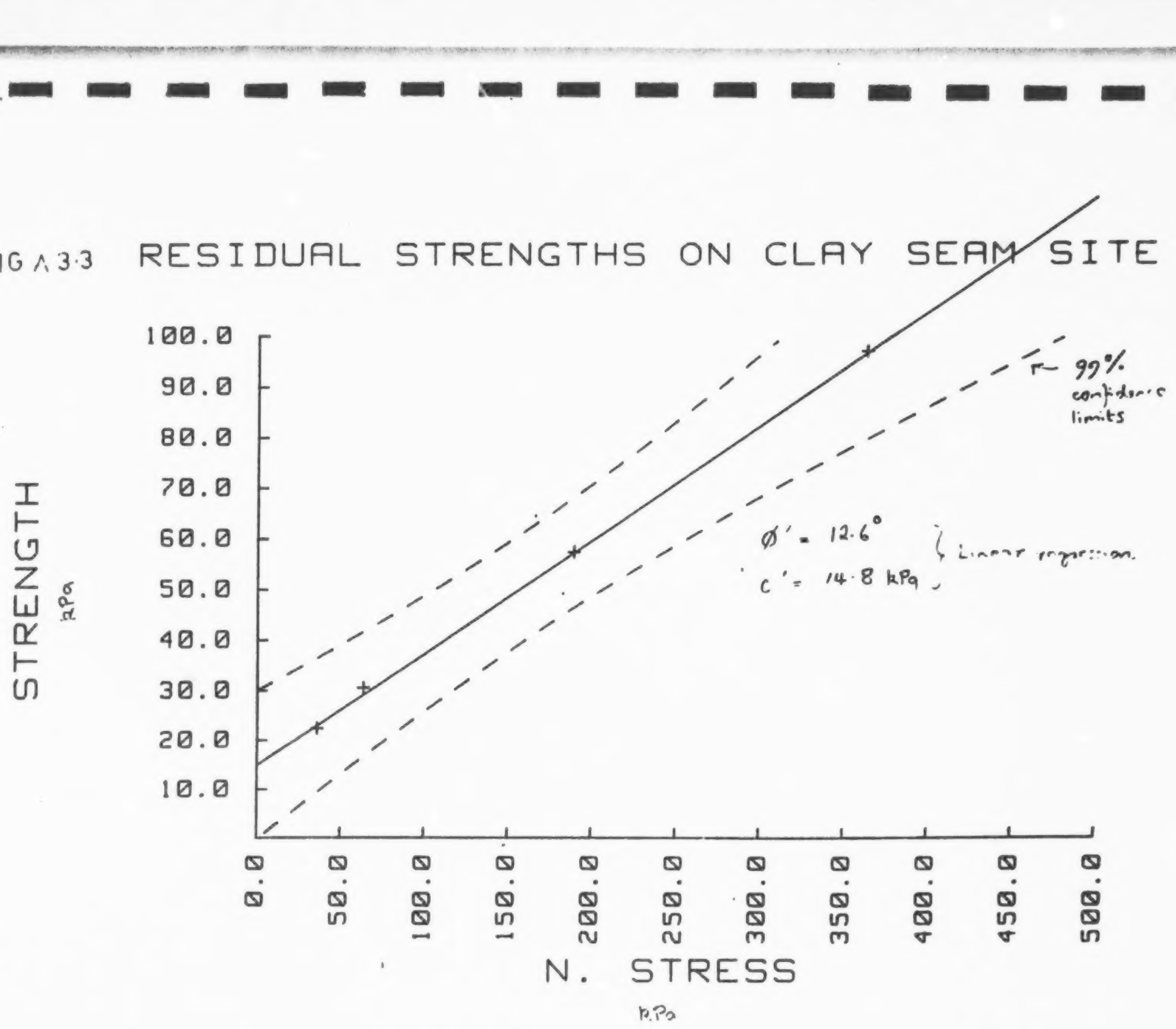


FIG A 3.3 RESIDUAL STRENGTHS ON CLAY SEAM SITE 1

APPENDIX 4

Ground Water information - Pit 03 - October 1983 to April 1984

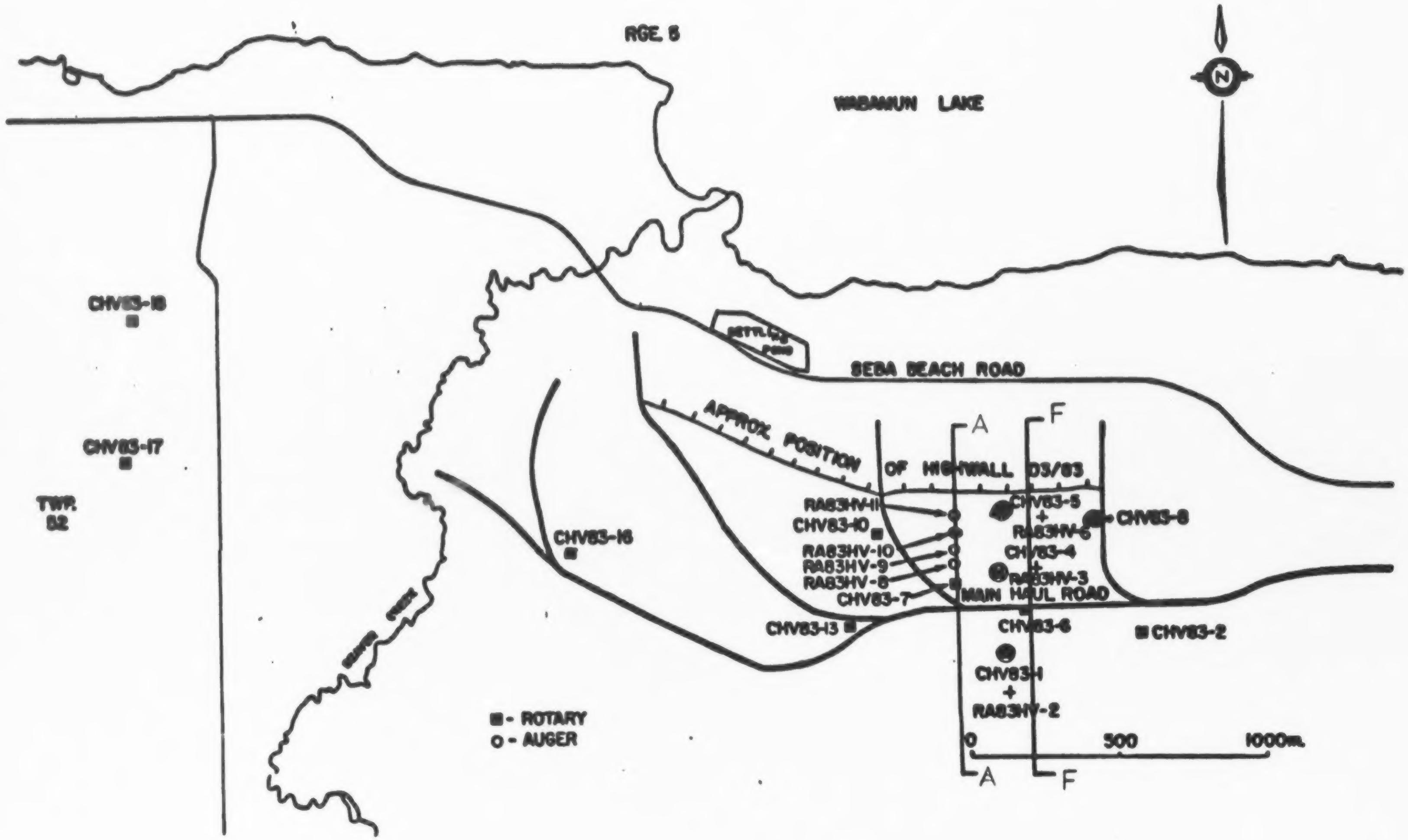
Piezometer installations

Twenty piezometers were installed (Fenton et a! (11)) to investigate the ground water conditions in the pit 03 area. Seven were completed in the overburden sandstone, eleven in coal seam No. 6 and one in coal seam No. 1. Figure A.4.1. shows the location of these piezometers and Table A.10 summarises the installation data.

Table A.11 gives the water level measurements during September 1983 for the piezometers installed in the sandstone unit. The hydraulic head distribution in the overburden sandstone is shown in the cross sections F-F and A-A (Figure A.4.1) given in Figures A.4.2. and A.4.3. respectively.

Fenton et al concluded that "these cross sections indicate that the water level is the overburden sandstone is within 1 to 5 metres of the ground surface at a distance of approximately 150 m from the highwall. This water level corresponds to vitually complete saturation of the overburden sandstone within several hundred metres of the pit 03 highwall. In addition, observations for September 1983, indicate that the hydraulic head in the overburden sandstone is stable, rather than declining as might be expected due to the close proximity of the highwall. Pre-mining water level data for the overburden sandstone in the pit 03 area is somewhat sparse, but indications are that very little change has occurred. Overall, the observations from the sandstone overburden suggest that poor drainage conditions exist in the overburden materials."

These conclusions are confirmed by a limited number of subsequent piezometer readings taken in December 1983, March and April 1984 and given in Table A12. From this table it is seen that very little change occurred during this period and that the mean water table elevation from all the readings is 741 m (standard deviation 1.01 m). If we take the mean elevation of the bentonitic clay band as approximately 726.2 m this gives a mean head above the bentonitic clay band of 14.8 m.


RGE. 5
WABAMUN LAKE
N
SETTLING POND
SEBA BEACH ROAD
APPROX. POSITION OF HIGHWALL 03/83
A
F
RA83HV-11
CHV83-10
RA83HV-10
RA83HV-9
RA83HV-8
CHV83-7
CHV83-5 + RA83HV-6
CHV83-8
CHV83-4 + RA83HV-3
MAIN HAUL ROAD
CHV83-6
CHV83-2
CHV83-13
CHV83-1 + RA83HV-2
CHV83-16
CHV83-18
CHV83-17
TWP. 52
■ - ROTARY
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0
500
1000m.
A
F

FIG A: 4.1 Location of piezometer installations. Piezometers installed in rotary holes are completed in coal seam number 6 (except CHV83-2, completed in seam number 1). Piezometers installed in augered holes are completed in the overburden sandstone.

TABLE A10

Summary of Highwall Stability Project Piezometer Installation Information.

WELL I.D.	SCREENED INTERVAL	STRATIGRAPHIC UNIT	ELEVATION G.S. (A.S.L.m.)	ELEVATION Top of Casing (A.S.L.m.)
C-HV83-1	50.6 -51.8	Coal Seam #6	757.43	758.086
C-HV83-2	38.1 -39.6	Coal Seam #1	755.91	756.756
C-HV83-4	41.0 -42.0	Coal Seam #6	750.66	751.572
C-HV83-5	30.0 -31.0	Coal Seam #6	742.16	743.08
C-HV83-6	47.6 -48.6	Coal Seam #6	754.24	755.203
C-HV83-7	47.2 -48.2	Coal Seam #6	754.43	755.600
C-HV83-8	40.5 -41.5	Coal Seam #6	752.21	752.287
C-HV83-10	34.8 -35.8	Coal Seam #6	743.55	744.514
C-HV83-11	58.2 -59.2	Coal Seam #6	764.57	765.171
C-HV83-13	40.3 -41.4	Coal Seam #6	746.84	747.979
C-HV83-16	18.3 -19.3	Coal Seam #6	732.78	733.601
C-HV83-17	36.24-37.50	Coal Seam #6	747.84	748.39
C-HV83-18	25.0 -26.0	Coal Seam #6	737.08	737.942
RA83-HV2	10.0 -11.0	S.S. Overburden	757.21	757.891
RA83-HV3	8.0 -9.0	S.S. Overburden	750.26	750.892
RA83-HV6	7.0 -8.0	S.S. Overburden	742.18	742.698
RA83-HV8	14.5 -15.5	S.S. Overburden	754.19	754.278
RA83-HV9	13.75-14.75	S.S. Overburden	752.97	752.99
RA83-HV10	17.7 -18.7	S.S. Overburden	748.89	748.98
RA83-HV11	14.0 -15.0	S.S. Overburden	744.89	744.991

TABLE A11

Water Level Measurements, Pit 03 Piezometers - in sandstone overburden -

WELL I.D.	SEPT. 1		SEPT. 14		SEPT. 21	
	DEPTH TO WATER(m)	HYDRAULIC HEAD*	DEPTH TO WATER(m)	HYDRAULIC HEAD*	DEPTH TO WATER(m)	HYDRAULIC HEAD*
RA83HV-2	DRY	746.89	DRY	746.89	DRY	746.89
RA83HV-3	9.05	741.84	9.07	741.82	9.09	741.80
RA83HV-6	2.27	740.43	2.26	740.44	2.27	740.43
RA83HV-8	12.47	741.81	12.49	741.79	12.49	741.79
RA83HV-9	11.20	741.79	11.20	741.79	11.21	741.78
RA83HV-10	9.64	739.34	9.50	739.48	9.46	739.52
RA83HV-11	6.68	738.01	6.83	738.16	6.83	738.16

* metres above sea level

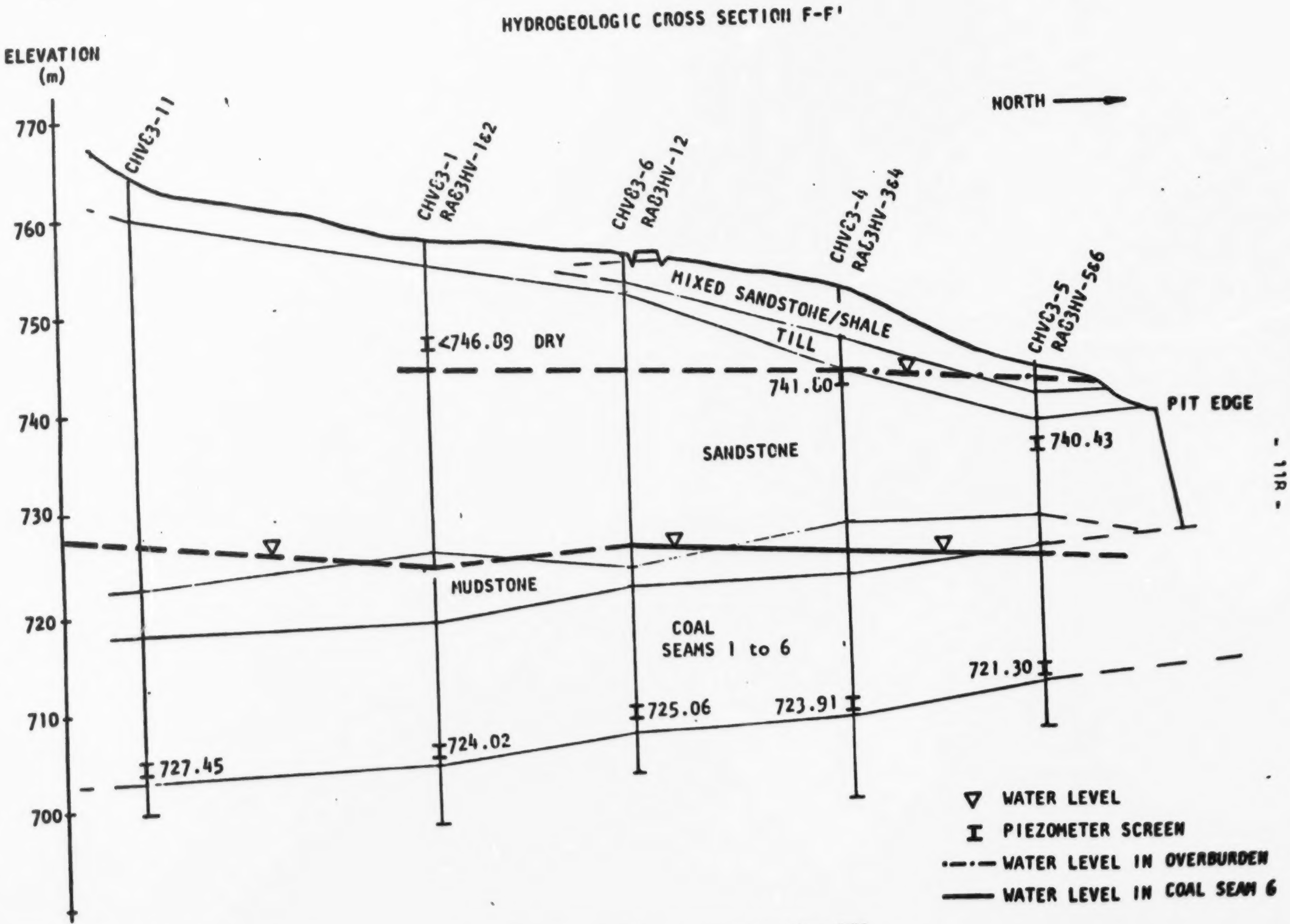

HYDROGEOLOGIC CROSS SECTION F-F'
ELEVATION (m)
770
760
750
740
730
720
710
700
NORTH
CHVE3-11
CHVE3-1 RAE3HV-1&2
CHVE3-6 RAE3HV-12
CHVE3-4 RAE3HV-3&4
CHVE3-5 RAE3HV-5&6
PIT EDGE
MIXED SANDSTONE/SHALE
TILL
<746.09 DRY
741.60
740.43
SANDSTONE
MUDSTONE
COAL SEAMS 1 to 6
721.30
725.06
723.91
724.02
727.45
▽ WATER LEVEL
I PIEZOMETER SCREEN
-·- WATER LEVEL IN OVERBURDEN
— WATER LEVEL IN COAL SEAM 6

FIG A 4·2

Piezometric surface cross section FF'.

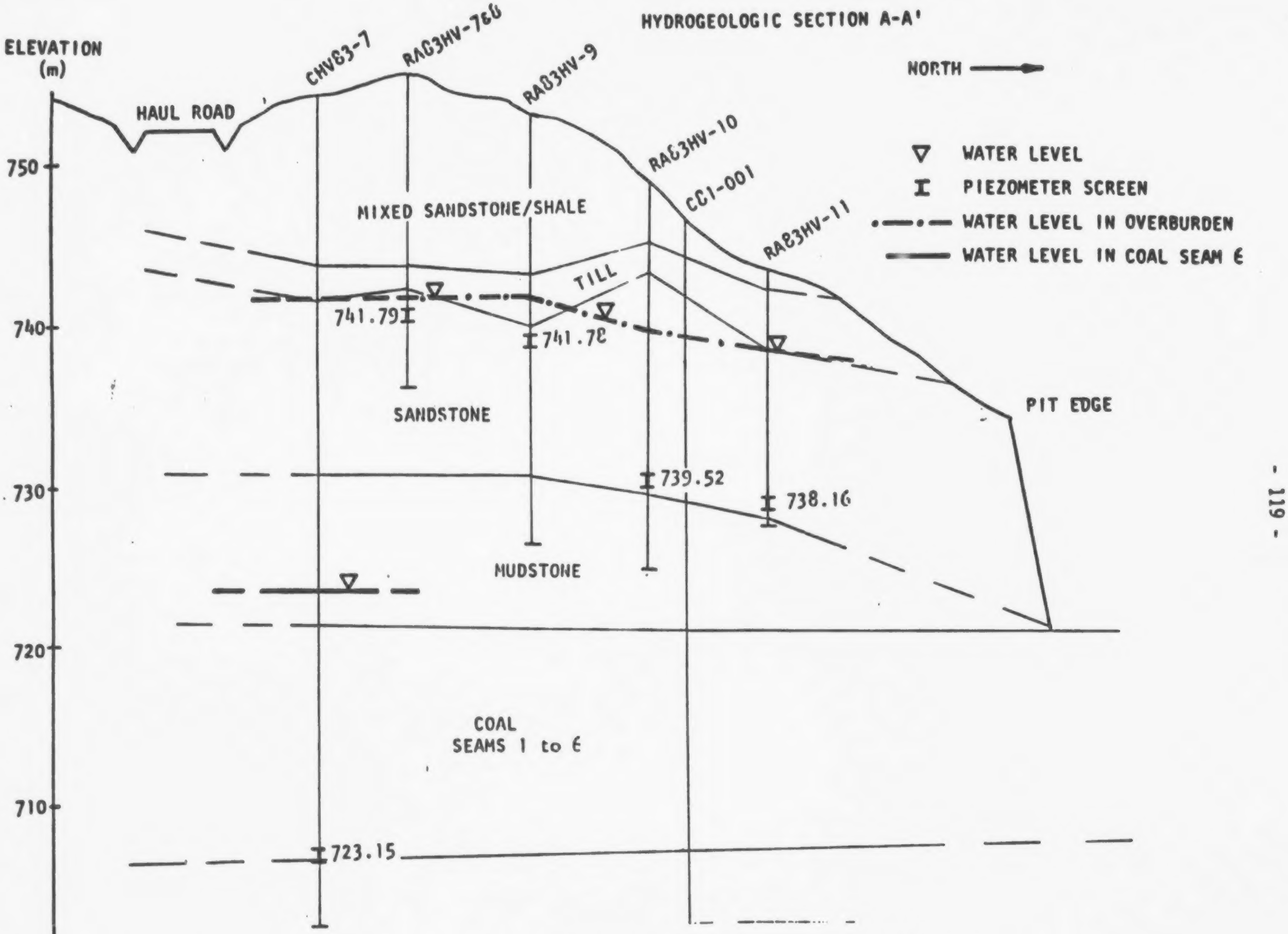

HYDROGEOLOGIC SECTION A-A'
NORTH
ELEVATION (m)
750
740
730
720
710
HAUL ROAD
CHV83-7
RA83HV-7&8
RA83HV-9
RA83HV-10
CC1-001
RA83HV-11
PIT EDGE
MIXED SANDSTONE/SHALE
TILL
SANDSTONE
MUDSTONE
COAL SEAMS 1 to 6
741.79
741.78
739.52
738.16
723.15
WATER LEVEL
PIEZOMETER SCREEN
WATER LEVEL IN OVERBURDEN
WATER LEVEL IN COAL SEAM 6

FIG A 4.3 Piezometric surface cross section AA'.

TABLE A12: SANDSTONE PIEZOMETERS

ction AA		Elevation Top of Collar (A.S.L.)	Sept. 21st/83 Depth to Water m	Head Elevation	Dec. 83 Depth to Water	Head Elevation	March 84 Depth to Water	Head Elevation	April 84 Depth to Water	Head Elevation
33-Hv	7	-	-	-	-	-	-	-	-	-
	8	754.28	12.48	741.80	12.53	741.75	12.58	741.70	12.66	741.62
	9	752.99	11.21	741.78	11.26	741.73	-	-	11.57	741.42
	10	748.98	9.46	739.52	9.45	739.53	9.506	739.47	9.616	739.37
	11	744.99	-	-	-	-	-	-	-	-
ean				741.03		741.00		740.58		740.80
D				1.3		1.27		1.58		1.25
ection FF										
A83-HV	1	-	-	-	-	-	-	-	-	-
	2	757.89	Dry	< 746.89	Dry	< 746.89	Dry	<746.89	Dry	<746.89
	3	750.89	9.09	741.80	9.13	741.76	9.7	741.19	9.185	741.70
	4	-	-	-	-	-	-	-	-	-
ain										
.D.										
oth section Mean				741.22		741.19		740.78		741.02
S.D.				1.13		1.108		1.17		1.11

lean water table elevation = 741.08 m
S.D. = 1.01 m

levation of bontinotic clay band ~=726.2m

lead above bontontic clay band = 14.8m

Estimation of the phraetic line near the pit.

Consider section 5+70 (Figure 31) as a typical cross section shown in Figure A.4.4. Assume that the water table is 1 or 5 m below surface at 120 m from the toe. Then if it is assumed that there is a linear drawdown, passing through the intersection of the bench with the toe of the upper slope, phraetic lines 3 and 4 are obtained and drawn on this figure. If it is assumed that drainage is poorer and the water table is maintained 1 and 5 m from surface to a distance 60 m from the toe and that (a) the drawdown is curvelinear passing through the toe of both slopes (line 2) or (b) that the drawdown is curvelinear but intersects the slope faces at half the slope height (line 1), then the phraetic lines 1 and 2 may be drawn on this figure.

Now for MBPSSF analysis we assume a horizontal water table over the affected area. From the table on Figure A.4.4. it is seen that the "average horizontal water table" between the toe and the crest (affected area) is given for each of these potential phractic lines as

Line 1: 11.0 m
Line 2: 7.5 m
Line 3: 8.0 m
Line 4: 8.0 m

It does not seem sensible to take line 1 as the phraetic surface where the average water table is above the bench height. The other three indicate an average in the 7-8 m head range. This will therefore be taken as the starting point for the water table height in the MBPSSF failure analysis.

It will be noted that this is close to the water table level assumed by the consultants in considering the failure of this slope in the previous year (case history #3).

LINE	WATER TABLE HEIGHT -m- ABOVE CLAY BAND 12.2 m	6.1 m	at crest	at lower face	mean
1	1	1	18	4	11
2	5	5	15	0	7·5
3	1	-	10	6	8
4	5	–	0	7	5

SECTION 5 + 70

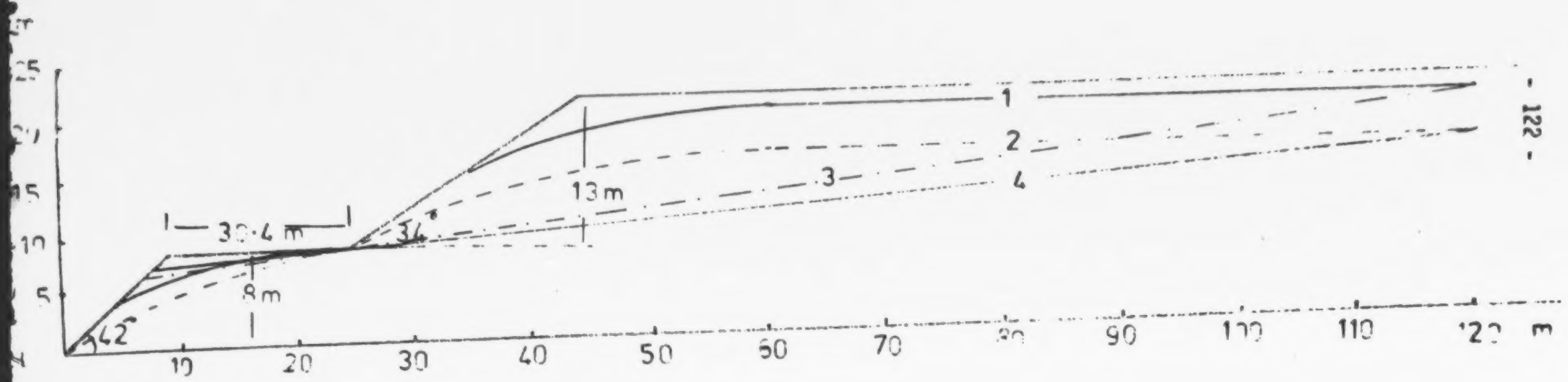

m
25
20
15
10
5
30·4 m
8m
13m
34°
42°
1
2
3
4
10
20
30
40
50
60
70
80
90
100
110
120
m

FIG A4·4 : ESTIMATED LIMITS OF PHREATIC LINE NEAR THE PIT

APPENDIX 5

MBPSSF Analysis - Highvale (1984)

Input Data

Four cross sections were selected for study, with the geometry as given in Figure 32 in the main text. The strength parameters chosen were

$c = 9.3$ kPa $\qquad \sigma = 25.4$ kPa

$\phi = 24.6^{\circ}$ $\qquad \sigma = 3.05^{\circ}$

The tensile strength T was assumed to be zero.

The angle of the failure plane with the horizontal was taken as -0.06°, $\sigma = 0.10^{\circ}$ (Appendix 1). Initially each section was analysed, in the deterministic mode, using the mean values given above for water table heights H_w of 7.0 and 8.0 metres. All solutions at 8.0 metres gave an infinite number and extent of cracking, whereas the deterministic solution at $H_w = 7.0$ metres gave a finite number and extent of cracking. Consequently, it is clear that in this range 7-8 metres is the "critical" range for extensive cracking and it was decided to perform the measuring analyses using $H_w = 7.0$ metres.

Twenty five runs in the probabalistic mode were run for each cross section under consideration. Tables A13, A14, A15 and A16 give the summary spread sheets for these runs.

Discussion

Examination of these tables shows that the total number of cracks occurring varies widely from a minimum of 4 to a maximum of 99 (program limit). Likewise many solutions produce an "infinite" number of cracks. i.e. the cracking extends beyond the program limit of 10 x the total slope height.

TABLE A13: SECTION 3+70, HW = 7.0 m - PROBABALISTIC ANALYSIS

SECTION 3+70

SUMMARY (LOWER LIMIT)
DISTANCE TO CRACK NUMBER

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	TOTAL # CRACKS	TOTAL EXTENT - m
RUN 1	9.360	12.810	16.230	19.650	23.040	26.460	29.880	33.270	36.660	47.160	48.120	49.230	50.400	51.690	16	54.39
RUN 2	7.560	11.430	14.310	17.190	20.070	22.950	25.830	28.710	31.590	34.500	45.700	46.590	47.490	48.450	23	60.24
RUN 3	9.240	12.990	16.680	20.430	24.150	27.930	31.680	35.490	46.710	48.090	49.560	51.120	52.740	54.450	21	65.85
RUN 4	9.870	12.990	16.110	19.230	22.350	25.470	28.590	31.710	34.830						9	34.83
RUN 5	12.450	17.100	21.720	26.340	30.960	35.580	47.500	49.080	50.700	52.410	54.150	55.950	57.810	59.730	15	61.71
RUN 6	6.690	9.990	12.420	14.850	17.280	19.710	22.140	24.570	27.000	29.430	31.860	34.290	36.690	46.350	26	57.15
RUN 7	5.700	8.970	12.210	14.850	16.950	19.320	21.690	24.060	26.460	28.830	31.200	33.570	35.940		13	35.94
RUN 8	4.380	7.230	9.780	11.790	13.800	15.810	17.820	19.860	21.900	23.940	25.980	28.020	30.060	32.100	25	58.64
RUN 9	18.510	23.430	28.290	33.150											4	33.15
RUN 10	10.350	14.160	18.000	21.810	25.620	29.430	33.270	37.110	47.950	48.810	50.160	51.600	53.100	54.690	23	67.65
RUN 11	7.920	11.850	14.700	17.550	20.430	23.280	26.160	29.040	31.920	34.800					10	34.8
RUN 12	5.190	8.460	11.550	13.950	16.350	18.750	21.180	23.580	25.980	28.380	30.780	33.210	35.640	45.270	25	57.15
RUN 13	9.180	12.630	16.050	19.470	22.890	26.310	29.730	33.150	36.570	47.040	48.150	49.320	50.610	51.960	20	61.32
RUN 14	12.330	17.850	23.310	28.830	34.380	47.250	49.470	51.780	54.150	56.520	58.950	61.410	63.990	65.790	99	240
RUN 15	5.700	9.090	11.610	14.130	16.650	19.170	21.690	24.210	26.730	29.250	31.770	34.320	36.840		13	36.84
RUN 16	5.670	9.090	11.640	14.190	16.740	19.290	21.840	24.390	26.940	29.490	32.040	34.590	37.140	46.000	23	56.04
RUN 17	22.230	30.330	47.910	50.340	52.860	55.380	57.930	60.450	63.000	64.830	66.660	68.490	70.320	72.150	99	224.9
RUN 18	11.850	15.990	20.070	24.150	28.230	32.310	36.390	47.670	48.900	50.220	51.600	53.100	54.660	56.280	82	130.27
RUN 19	15.420	19.500	23.550	27.630	31.680	35.730	48.060	48.930	49.890	50.940	52.080	53.280	54.570	55.950	16	58.89
RUN 20	13.410	18.990	24.480	30.000	35.520	47.790	49.770	51.840	53.970	56.100	58.320	60.540	62.790	64.410	99	190.15
RUN 21	2.430	4.560	6.420	8.190	9.990	11.490	12.990	14.490	15.990	17.490	18.990	20.490	21.990	23.490	23	37.05
RUN 22	8.310	12.420	15.390	18.330	21.270	24.210	27.180	30.150	33.120	36.090					10	36.09
RUN 23	6.870	10.680	13.650	16.590	19.530	22.470	25.410	28.350	31.290	34.230	37.170	46.500	47.550	48.660	23	61.56
RUN 24	11.880	16.170	20.430	24.690	28.950	33.210	46.740	48.000	49.350	50.790	52.290	53.880	55.530	57.240	14	57.24
RUN 25	15.750	21.750	27.720	33.690	47.760	49.740	51.840	54.000	56.220	58.440	60.750	63.090	64.710	66.330	99	210.06
MEAN	9.930	14.01	18.17	21.63	24.89	28.71	32.7	35.57	38.64	41.64	44.58	46.79	48.59	52.68	33.20	81.19
S.D.	4.650	5.73	8.34	8.97	10.19	11.51	12.63	12.67	12.74	12.05	13.02	12.79	12.67	11.61	32.45	64.72
# CASES	25	25	25	25	24	24	24	24	24	23	21	21	21	19	25	25

TABLE A14: SECTION 5+70, HW = 7.0 m - PROBABILISTIC ANALYSES

SECTION 5+70	SUMMARY (LOWER LIMIT) DISTANCE TO CRACK NUMBER														TOTAL #CRACKS	MAX EXTENT OF CRACKING
	1	2	3	4	5	6	7	8	9	10	11	12	13	14		
RUN 1	9.700	13.600	17.490	21.330	25.170	29.010	32.050	36.660	46.770	48.630	50.550	52.530	54.540	56.900	15	58.65
RUN 2	7.770	11.970	15.150	18.330	21.510	24.690	27.070	31.050	34.290	37.500	46.500	48.150	49.920	51.720	10	59.46
RUN 3	9.630	13.770	17.940	22.000	26.200	30.450	34.600	38.000	47.610	49.060	52.170	54.510	56.000	59.200	99	199.53
RUN 4	10.470	14.040	17.500	21.120	24.660	28.200	31.740	35.200	38.020	47.640	49.290	51.000	52.030	54.690	16	58.53
RUN 5	13.600	19.020	24.330	29.640	34.950	47.160	49.620	52.000	54.540	57.000	59.490	61.050	62.610	64.170	99	197.9
RUN 6	6.040	10.320	13.020	15.690	18.360	21.030	23.700	26.370	29.040	31.710	34.300	37.050			12	37.05
RUN 7	5.020	9.150	11.750	14.310	16.090	19.470	22.000	24.660	27.240	29.020	32.400	34.900	37.560	45.070	91	131.0
RUN 8	4.440	7.350	9.990	12.100	14.370	16.560	18.750	20.940	23.130	25.320	27.510	29.700	31.090	34.110	24	55.30
RUN 9	23.640	29.700	35.670	40.330	50.460	52.600	54.900	57.150							8	57.15
RUN 10	10.900	15.330	19.650	23.970	28.290	32.640	36.960	47.220	49.350	51.510	53.760	56.010	58.260	60.660	41	90.73
RUN 11	0.160	12.400	15.690	18.070	22.050	25.230	28.410	31.650	34.060	38.070					10	38.07
RUN 12	5.200	8.500	11.050	14.490	17.070	19.650	22.260	24.870	27.400	30.090	32.700	35.340	37.950	45.700	21	57.40
RUN 13	9.570	13.410	17.250	21.090	24.930	28.000	32.640	36.400	46.650	48.570	50.500	52.620	54.690	56.790	15	58.92
RUN 14	13.320	19.560	25.770	32.010	38.200	40.330	51.400	54.570	57.600	60.690	62.760	64.030	66.900	69.000	77	210 *
RUN 15	5.790	9.270	12.000	14.730	17.460	20.190	22.920	25.650	28.300	31.140	33.070	36.600	45.420	46.920	23	61.30
RUN 16	5.760	9.270	12.030	14.790	17.550	20.310	23.070	25.030	28.590	31.350	34.110	36.070			12	36.07
RUN 17	20.200	30.070	49.710	53.220	56.950	59.790	61.950	64.110	66.270	68.430	70.560	72.690	74.020	76.950	77	210 *
RUN 18	12.960	17.700	22.410	27.120	31.830	36.540	47.460	49.990	51.010	54.030	56.200	58.530	60.930	62.200	17	66.33
RUN 19	10.400	23.460	28.350	33.240	38.130	40.400	50.340	52.320	54.330	56.370	58.470	60.690			12	60.69
RUN 20	14.760	21.150	27.400	33.700	47.040	50.040	52.950	55.000	58.620	60.400	62.340	64.200	66.060	67.920	92	210 *
RUN 21	2.460	4.990	6.400	8.250	10.000	11.640	13.200	14.020	16.410	18.000	19.590	21.100	22.770	24.360	34	95.95
RUN 22	0.610	13.230	16.530	19.000	23.130	26.430	29.730	33.030	36.330	46.320	47.940	49.600	51.400	53.340	14	53.34
RUN 23	7.020	11.070	14.200	17.490	20.700	23.910	27.120	30.330	33.540	36.750	45.900	47.640	49.500	51.360	36	81.99
RUN 24	12.960	17.000	22.770	27.660	32.920	37.410	47.760	50.010	52.260	54.570	56.000	59.220	60.630	62.040	71	142.41
RUN 25	10.150	25.200	32.160	39.100	50.250	53.250	56.190	59.070	60.930	62.050	64.740	66.630	68.520	70.410	85	210 *
MEAN	10.90	15.57	19.01	24.11	28.34	32.47	36.02	39.14	41.07	44.06	47.94	49.32	53.2	55.71	40.76	100.3
S.D.	6.09	7.59	9.26	11.06	12.44	13.51	13.04	13.07	13.60	13.51	13.41	13.09	13.00	12.46	33.4	65.66
# CASES	25	25	25	25	25	25	25	25	24	24	23	22	20	20	25	25

* CRACKING CONTINUES - LIMIT 10 X SLOPE WEIGHT INVOLVED.

TABLE A15: SECTION 6+70, HW = 7.0 m - PROBABALISTIC ANALYSIS

SECTION 6+70

SUMMARY (LOWER LIMIT)
DISTANCE TO CRACK NUMBER

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	TOTAL # CRACKS	TOTAL EXTENT OF CRACKING - m
RUN 1	9.390	13.410	17.340	21.300	25.260	29.220	33.180	37.140	41.070	46.920	50.400	53.490	54.960	56.430	36	88.77
RUN 2	7.440	11.820	15.120	18.390	21.660	24.930	28.200	31.470	34.740	38.070	41.370	46.620	49.890	52.000	29	73.50
RUN 3	9.240	13.530	17.020	22.000	26.400	30.690	35.040	39.390	46.320	50.250	53.640	55.410	57.100	58.950	70	100.00 *
RUN 4	10.020	13.710	17.400	21.090	24.780	28.470	32.160	35.850	39.540	46.350	49.030	52.030	54.120	55.410	76	135.39
RUN 5	13.350	18.900	24.240	29.940	35.460	40.900	47.640	51.630	55.350	57.210	59.070	60.930	62.790	64.650	76	100.00 *
RUN 6	6.600	10.710	12.930	15.660	18.390	21.120	23.850	26.580	29.310	32.040	34.740	37.470	40.200	42.930	16	49.95
RUN 7	5.640	8.940	11.580	14.220	16.860	19.500	22.140	24.780	27.450	30.090	32.730	35.370	38.010	40.650	17	51.45
RUN 8	4.350	7.170	9.900	12.150	14.370	16.590	18.810	21.030	23.250	25.470	27.690	29.910	32.130	34.350	17	41.40
RUN 9	24.100	30.630	36.960	47.010	51.120	54.750	56.340	57.900	59.460	61.020	62.580	64.140	65.700	67.260	87	100.00 *
RUN 10	10.590	15.090	19.560	24.030	28.500	32.970	37.470	41.970	47.500	51.210	54.600	56.200	57.930	59.500	85	100.00 *
RUN 11	7.000	11.100	14.370	17.640	20.910	24.180	27.450	30.700	34.000	37.300	40.600	46.300	49.710	52.620	26	60.82
RUN 12	5.160	8.400	11.040	13.680	16.320	18.990	21.630	24.270	26.940	29.610	32.280	34.950	37.620	40.320	37	79.99
RUN 13	9.150	13.140	17.100	21.060	25.020	28.980	32.970	36.930	40.890	46.030	50.370	53.550	55.000	56.610	94	100.00 *
RUN 14	13.050	19.500	25.920	32.370	38.850	47.130	51.750	56.070	58.500	60.960	63.450	65.910	68.370	70.860	56	100.00 *
RUN 15	5.640	9.090	11.880	14.670	17.460	20.250	23.040	25.830	28.620	31.440	34.230	37.020	39.840	42.660	29	60.34
RUN 16	5.610	9.090	11.910	14.730	17.550	20.370	23.190	26.010	28.830	31.650	34.470	37.290	40.110	42.930	17	52.59
RUN 17	29.160	39.630	40.010	53.700	56.340	58.950	61.560	64.170	66.780	69.360	71.970	74.580	77.190	79.800	53	100.00 *
RUN 18	12.600	17.550	22.440	27.330	32.220	37.110	42.000	47.790	51.400	54.930	56.550	58.170	59.790	61.410	87	100.00 *
RUN 19	18.420	23.640	28.000	33.960	39.120	47.160	50.940	54.270	55.650	57.030	58.410	59.790	61.170	62.550	99	100.00 *
RUN 20	14.520	21.120	27.690	34.260	40.800	47.970	52.260	54.480	56.700	58.920	61.140	63.360	65.580	67.800	66	100.00 *
RUN 21	2.430	4.530	6.390	8.190	9.780	11.370	12.960	14.550	16.140	17.730	19.320	20.910	22.500	24.090	27	47.31
RUN 22	8.190	11.580	14.970	18.390	21.780	25.170	28.560	31.950	35.340	38.790	42.210	47.130	50.400	53.340	15	54.69
RUN 23	6.010	10.950	14.250	17.550	20.850	24.150	27.450	30.750	34.050	37.300	40.600	46.200	49.500	52.440	66	120.91
RUN 24	12.600	17.730	22.800	27.870	32.940	38.010	46.300	50.430	53.910	55.620	57.330	59.040	60.750	62.460	85	100.00 *
RUN 25	19.060	25.440	32.730	40.050	48.030	52.500	54.750	57.000	59.250	61.500	63.780	66.060	68.340	70.650	61	100.00 *
MEAN	10.8	15.43	19.76	24.05	28.03	32.06	35.67	38.92	42.04	45.11	47.74	50.51	52.75	54.94	53.9	124.04
S.D.	6.29	7.97	9.67	11.2	12.15	13.15	13.59	13.77	13.77	13.64	13.5	13.19	13.01	12.07	29.6	50.0
# CASES	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25

* CRACKING CONTINUES - LIMIT 10X SLOPE HEIGHT INVOLVED.

TABLE A16: SECTION 0+40, HW = 7.0 m - PROBABILISTIC ANALYSIS

SECTION 0+40

SUMMARY (LOWER LIMIT)
DISTANCE TO CRACK NUMBER

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	TOTAL # CRACKS	TOTAL EXTENT CRACKING - m
RUN 1	11.790	16.030	20.370	23.000	27.360	30.870	34.300	37.090	41.370	44.050	48.330	52.000	58.600	60.240	86	170.00 *
RUN 2	8.050	13.110	17.370	20.310	23.280	26.250	29.220	32.190	35.160	38.130	41.100	44.070	47.040	51.700	91	170.00 *
RUN 3	11.400	16.710	20.550	24.420	28.260	32.130	36.030	39.900	43.830	47.730	52.740	58.920	60.010	62.700	67	170.00 *
RUN 4	12.900	17.940	21.100	24.390	27.600	30.810	34.020	37.230	40.440	43.650	46.860	52.000	58.170	59.550	87	160.29
RUN 5	15.930	20.730	25.500	30.270	35.040	39.810	44.580	51.870	58.860	60.840	62.820	64.800	66.780	68.760	65	170.00 *
RUN 6	7.740	11.460	14.910	17.400	19.860	22.320	24.780	27.240	29.700	32.160	34.620	37.080	39.540	42.000	83	136.06
RUN 7	6.360	10.000	13.320	16.740	19.170	21.600	24.030	26.460	28.890	31.320	33.750	36.180	38.610	41.040	99	160.35
RUN 8	4.600	8.040	10.770	13.440	16.290	18.360	20.430	22.500	24.570	26.640	28.740	30.810	32.880	34.950	22	56.01
RUN 9	25.170	30.360	35.460	40.560	45.660	52.770	60.030	61.710	63.390	65.070	66.750	68.430	70.110	71.790	73	170.00 *
RUN 10	13.230	19.200	23.130	27.090	31.020	34.950	38.910	42.870	46.860	52.380	58.740	60.510	62.280	64.050	73	170.00 *
RUN 11	9.400	13.710	16.680	19.620	22.560	25.500	28.440	31.380	34.350	37.320	40.290	43.260	46.230	51.420	28	76.05
RUN 12	5.640	9.390	12.570	15.780	18.240	20.700	23.160	25.620	28.080	30.540	33.030	35.490	37.950	40.410	26	66.45
RUN 13	11.430	16.410	19.950	23.460	26.970	30.480	34.020	37.560	41.100	44.640	48.180	52.770	58.600	60.360	81	170.00 *
RUN 14	15.300	20.970	26.640	32.340	38.070	43.770	51.010	59.250	61.890	64.500	67.140	69.780	72.450	75.090	49	170.00 *
RUN 15	6.270	10.140	13.530	17.100	19.680	22.260	24.840	27.420	30.000	32.580	35.160	37.740	40.320	42.900	52	105.06
RUN 16	6.240	10.110	13.530	17.100	19.710	22.290	24.870	27.450	30.030	32.610	35.190	37.770	40.350	42.930	99	170.00 *
RUN 17	28.560	37.050	45.390	53.910	62.130	64.950	67.770	70.590	73.410	76.230	79.050	81.870	84.690	87.510	44	170.00 *
RUN 18	15.360	19.620	23.850	28.080	32.310	36.540	40.770	45.000	51.010	58.560	60.300	62.040	63.700	65.520	74	170.00 *
RUN 19	20.910	25.170	29.400	33.630	37.890	42.120	46.350	52.620	59.460	60.930	62.400	63.870	65.340	66.810	40	105.03
RUN 20	16.800	22.530	28.230	33.930	39.630	45.330	52.590	59.760	62.160	64.530	66.900	69.270	71.610	73.980	95	170.00 *
RUN 21	2.490	4.740	6.810	8.730	10.530	12.300	14.190	15.720	17.250	18.780	20.310	21.840	23.370	24.900	33	58.98
RUN 22	10.140	14.460	17.520	20.550	23.580	26.610	29.640	32.670	35.730	38.790	41.850	44.910	47.970	52.300	17	61.02
RUN 23	7.770	12.090	16.050	19.000	22.000	25.000	28.000	31.000	34.000	37.000	40.000	43.000	46.000	49.000	88	170.00 *
RUN 24	15.270	19.710	24.120	28.530	32.940	37.290	41.670	46.050	52.320	58.950	60.750	62.900	64.410	66.210	72	170.00 *
RUN 25	20.100	26.340	32.520	38.730	44.940	52.000	60.330	62.790	65.220	67.650	70.080	72.540	75.000	77.460	51	170.00 *
MEAN	12.39	17.07	21.17	24.96	28.99	32.71	36.59	40.19	43.59	46.65	49.41	52.10	54.93	57.35	62.2	141.5
S.D.	6.46	7.45	8.63	9.81	11.37	12.46	13.70	14.59	15.09	15.31	15.33	15.29	15.28	15.13	24.9	43.8
# CASES	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25

* CRACKING CONTINUES - LIMIT 10X SLOPE HEIGHT INVOLVED

It is then clear, as was discussed also in case history, No. 3, that the location of individual crack sets and the number of individual crack sets is so variable that "mean positions" etc. would be virtually meaningless. What is more important is the total extent of fracturing, i.e. how far back into the crest does cracking extend, regardless of the number of cracks.

Figure A.5.1 shows a plan of the failed area and marks the total OBSERVED extent of cracking. Also marked on this figure is the "mean maximum" extent of cracking from the analyses for each section plus the standard deviations.

(NOTE: the "mean extent" of cracking includes runs where the cracking extends to infinity. In these cases it was assumed that the extent was 10 times the slope height, in order to calculate this mean).

It is seen that the calculated solutions do in fact bracket the observed maximum extent of cracking, although the standard deviations are large.

It is also noted that the "mean extent of cracking" calculated for section 3 + 70, 5 + 70 and 6 + 70 tend to parallel the observed trend of the cracks (i.e. cutting back towards the slope face at the east end). This is not the case for section 8 + 40 where the observed cracking curves back towards the slope face but the analysis would predict a greater extent of cracking. The reducing total overburden from East to West accounts for this calculated trend; the reduced extent of observed cracking at section 8 + 40 is therefore contrary to theory and it must be assumed that perhaps some change in lithology occurs close to this section. This should be investigated further at a suitable opportunity.

Probability of cracking extending beyond Xi metres from the toe (H_W = 7.0 m)

From the summary spread sheets for each section, Table A17 was prepared. This table shows the number of cases (out of 25 runs) in which the extent of cracking exceeded a given value Xi metres from the toe. The probability of cracking extending beyond Xi metres was then determined and

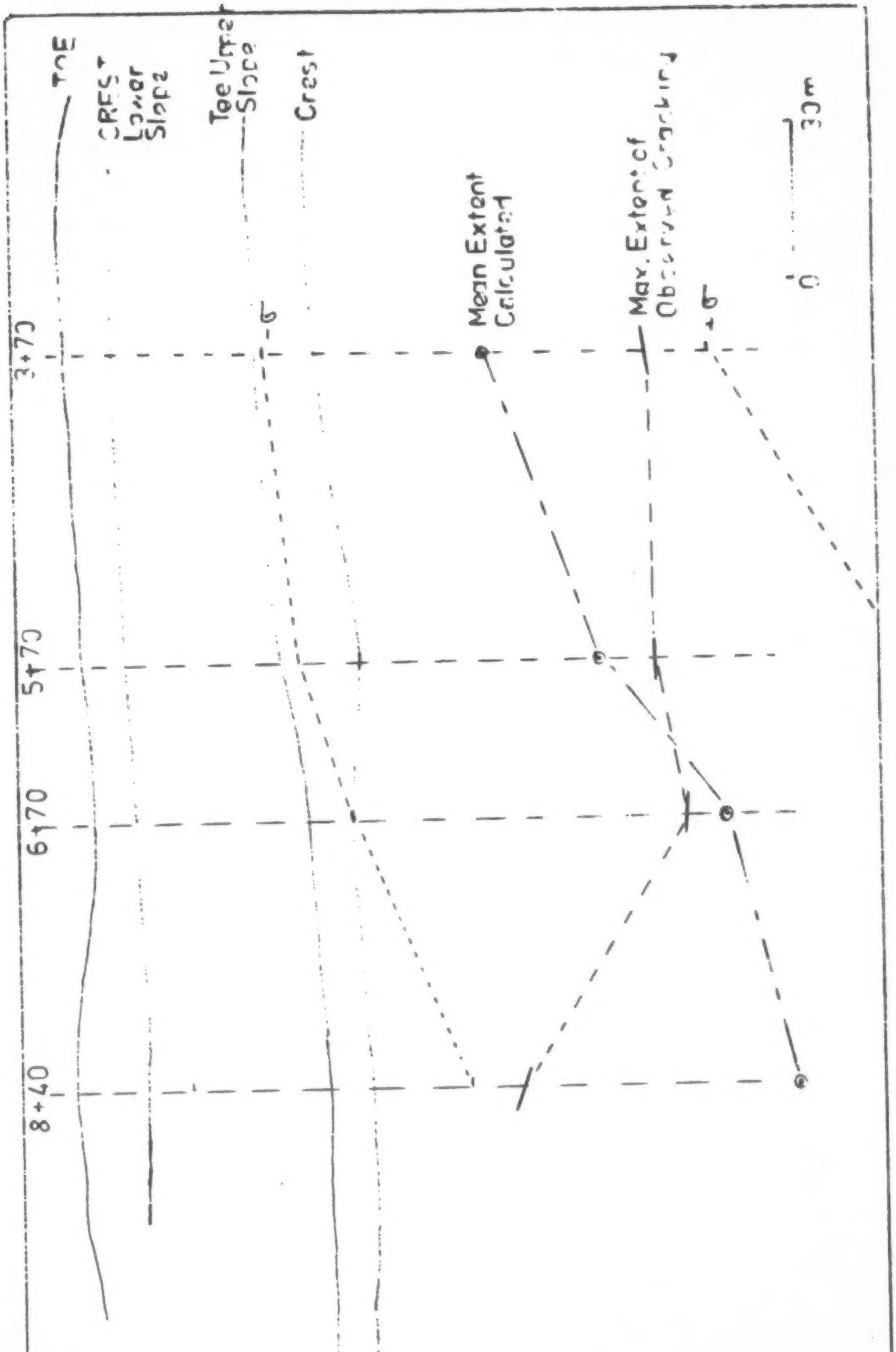


FIG A5.1: Observed and Calculated Extent of Cracking

TABLE A17: PROBABILITY OF CRACKING EXTENDING BEYOND Xi METRES FROM THE TOE ($H_w = 7.0$ m)

(25 runs for each section)

Xi m	Section 3 + 70 #cases Xi	Section 3 + 70 % Prob.	Section 5 + 70 # cases Xi	Section 5 + 70 % Prob.	Section 6 + 70 # cases Xi	Section 6 + 70 % Prob.	Section 8 + 40 # cases Xi	Section 8 + 40 % Prob.
10	25	100	25	100	25	100	25	100
20	25	100	25	100	25	100	25	100
30	25	100	25	100	25	100	25	100
40	18	72	22	88	25	100	25	100
50	18	72	22	80	22	88	25	100
60	11	44	13	52	19	76	23	92
70	6	24	10	40	17	68	21	82
80	6	24	10	40	15	60	20	80
90	6	24	9	36	14	52	20	80
100	6	24	8	32	14	52	20	80
125	6	24	8	32	14	52	18	72
150	5	20	6	24	12	48	17	68
175	5	20	6	24	12	48	16	64

has been plotted in Figure A.5.2.

It is seen from the figure that the probability of cracking up to about 25 metres from the toe is 100% for all sections. The probability of cracking extending beyond the upper crest (between 35 - 50 m from the toe depending on the sections) is at least 60% for the most stable section 3 + 70.

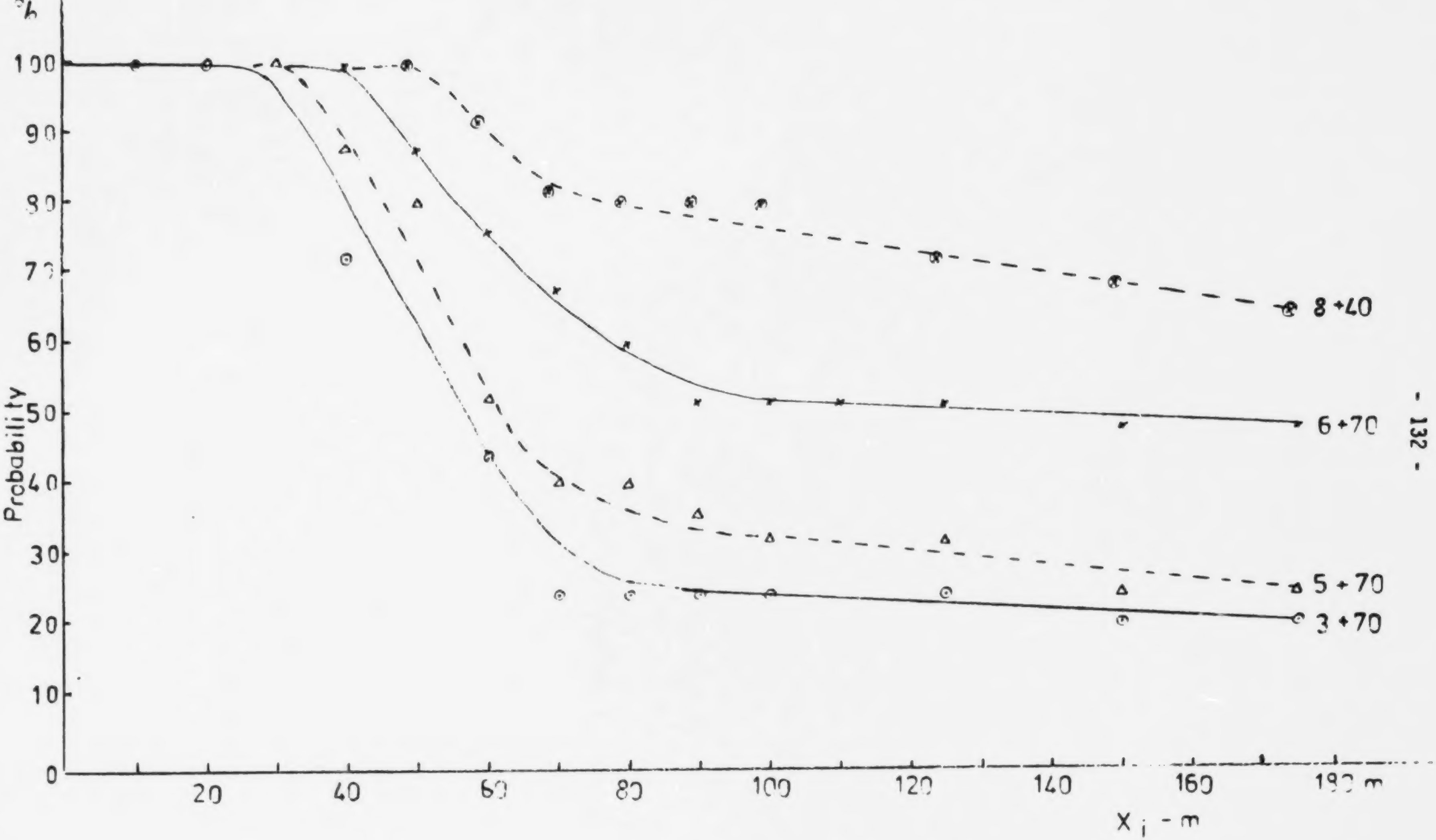


FIG A5.2 : PROBABILITY OF CRACKING EXTENDING BEYOND X_i METRES FROM THE TOE

Effect of lowering the water table

From the point of view of controlling or perhaps eliminating failure, the most logical control method would be to attempt to lower the water table by drainage. This affect was ascertained in detail for section 5 + 70 only.

Twenty five probabalistic runs were carried out for section 5 + 70 with the water table height H_w varied from 1.5 m to 8.0 m. Tables A18 to A23 give the summary spread sheets for each of these probabalistic runs.

From the tables, table A24 was constructed which shows the probability of cracking extending beyond Xi metres for each of the water table levels. Figure A.5.2. shows a graph of these results.

From this graph, a second graph. (Figure A.5.3) may be drawn showing the probability of failure extending beyond specific "key distances" versus the water table level. In this case the "key" distances chosen were the distance from the toe of (a) the top of the lower slope, (b) the bottom of the upper slope and (c) the upper crest.

This latter graph can be used for design purposes. For example, suppose it was a basic design consideration that whilst failure in the lower slope could be tolerated, the probabilities of the failure extending onto the draline bench should be low. Then if the design requirement was that the probability of failure extending onto the dragline bench was 10% the water table must be lowered from 7 m to 1.9 m (see Figure A.5.3). Alternatively, if it was deemed that an acceptable design probability of failure extending onto the dragline bench was 30% then the water table need only be lowered to 2.5 m.

This graph clearly emphasises the exceptional sensitivity of this failure mode to the water table level.

TABLE A18: SECTION 5 + 70 $H_w = 1.5$ m

TEST CASE #4 - HIGHVALE CMRC - SECTION 5 + 70 ($H_w = 1.5$ m)

Summary (lower limit)

Run #	Distance to crack number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total # of Cracks	Total Extent of Cracking m
Run 1	No solution found - Factor of safety =						243.841								0	0
Run 2	No solution found - Factor of safety =						-377.843								0	0
Run 3	No solution found - Factor of safety =						-82.044								0	0
Run 4	No solution found - Factor of safety =						*******								0	0
Run 5	No solution found - Factor of safety =						-588.913								0	0
Run 6	No solution found - Factor of safety =						1827.352								0	0
Run 7		0.400													1	0.4
Run 8	No solution found - Factor of safety =						*******								0	0
Run 9	No solution found - Factor of safety =						-854.719								0	0
Run 10	No solution found - Factor of safety =						-233.524								0	0
Run 11		1.000													1	1.0
Run 12	No solution found - Factor of safety =						-237.520								0	0
Run 13	No solution found - Factor of safety =						-782.302								0	0
Run 14	No solution found - Factor of safety =						-67.853								0	0
Run 15	No solution found - Factor of safety =						-405.739								0	0
Run 16	No solution found - Factor of safety =						*******								0	0
Run 17	No solution found - Factor of safety =						359.575								0	0
Run 18	No solution found - Factor of safety =						*******								0	0
Run 19	No solution found - Factor of safety =						*******								0	0
Run 20	No solution found - Factor of safety =						295.143								0	0
Run 21	No solution found - Factor of safety =						-380.555								0	0
Run 22	1.250	1.950													2	1.95
Run 23	No solution found - Factor of safety =						*******								0	0
Run 24	No solution found - Factor of safety =						429.388								0	0
Run 25	No solution found - Factor of safety =						-123.376								0	0

TABLE A19: SECTION 5 + 70 $H_w = 2$ m

TEST CASE #4 - HIGHVALE CMRC - SECTION 5 + 70 ($H_w = 2$ m)

Summary (lower limit)

Run #	Distance to crack number 1	2	3	4	5	6	7	8	9	10	11	12	13	14	Total # of Cracks	Total Extent of Cracking m
Run 1	No solution found - Factor of safety =						229.698								0	0
Run 2	No solution found - Factor of safety =						-415.502								0	0
Run 3	No solution found - Factor of safety =						-84.186								0	0
Run 4		3.750													1	3.75
Run 5	No solution found - Factor of safety =						-723.732								0	0
Run 6		1.050													1	1.05
Run 7	No solution found - Factor of safety =						*******								0	0
Run 8		0.450													1	0.45
Run 9		8.600													1	8.6
Run 10		3.400													1	3.4
Run 11	No solution found - Factor of safety =						-222.033								0	0
Run 12	No solution found - Factor of safety =						-251.552								0	0
Run 13	No solution found - Factor of safety =						-985.991								0	0
Run 14	3.750	5.100													2	5.1
Run 15	No solution found - Factor of safety =						-447.982								0	0
Run 16		0.650													1	0.65
Run 17	No solution found - Factor of safety =						309.214								0	0
Run 18	No solution found - Factor of safety =						*******								0	0
Run 19	No solution found - Factor of safety =						*******								0	0
Run 20	No solution found - Factor of safety =						265.244								0	0
Run 21	No solution found - Factor of safety =						-408.807								0	0
Run 22	No solution found - Factor of safety =						-232.157								0	0
Run 23	No solution found - Factor of safety =						*******								0	0
Run 24	No solution found - Factor of safety =						381.501								0	0
Run 25	6.400	7.650	8.750												3	8.75

TABLE A20: SECTION 5+70 HW = 3.0 m

TEST CASE 04 - HIGHVALE CMRC - SECTION 5+70 (HW = 3m)

SUMMARY (LOWER LIMIT)
DISTANCE TO CRACK NUMBER

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	TOTAL # CRACKS	EXTENT m
RUN 1	4.000	5.650	7.050												3	7.05
RUN 2	2.450														1	2.45
RUN 3	3.600	5.300	6.750												3	6.75
RUN 4	5.050														1	5.05
RUN 5	6.300	8.100													2	8.10
RUN 6	2.050														1	2.05
RUN 7	1.450	2.550	3.500												3	3.50
RUN 8	NO SOLUTION FOUND - FACTOR OF SAFETY = ********														0	0.00
RUN 9	NO SOLUTION FOUND - FACTOR OF SAFETY = ********														0	0.00
RUN 10	4.050	6.550													2	6.55
RUN 11	NO SOLUTION FOUND - FACTOR OF SAFETY = -261.506														0	0.00
RUN 12	NO SOLUTION FOUND - FACTOR OF SAFETY = -302.700														0	0.00
RUN 13	42.000														1	42.00
RUN 14	5.450														1	5.45
RUN 15	1.400	2.500	3.450												3	3.45
RUN 16	NO SOLUTION FOUND - FACTOR OF SAFETY = 1554.727														0	0.00
RUN 17	10.000	11.400	12.000	14.200	15.600	17.000	18.400	19.800	21.200	22.600	24.000	25.400	26.800	28.200	> 14	> 28.20
RUN 18	NO SOLUTION FOUND - FACTOR OF SAFETY = 2049.772														0	0.00
RUN 19	8.050	10.650													2	10.65
RUN 20	6.350	8.300	10.050												3	10.05
RUN 21	NO SOLUTION FOUND - FACTOR OF SAFETY = -517.440														0	0.00
RUN 22	3.200	4.700	6.000	7.200											4	7.20
RUN 23	1.900	3.200													2	3.20
RUN 24	NO SOLUTION FOUND - FACTOR OF SAFETY = 287.043														0	0.00
RUN 25	7.900														1	7.90

TABLE A21: SECTION 5+70 HW = 4.0 m

TEST CASE 04 - HIGHVALE CMRC - SECTION 5+70 (HW = 3m)

SUMMARY (LOWER LIMIT)
DISTANCE TO CRACK NUMBER

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	TOTAL # CRACKS	EXTENT m
RUN 1	5.450	7.650	9.550												3	9.55
RUN 2	3.700	5.700													2	5.70
RUN 3	5.100	7.400	9.350												3	9.35
RUN 4	6.350														1	6.35
RUN 5	7.000														1	7.00
RUN 6	NO SOLUTION FOUND - FACTOR OF SAFETY = 461.940														0	0.00
RUN 7	2.400														1	2.40
RUN 8	NO SOLUTION FOUND - FACTOR OF SAFETY = 1617.070														0	0.00
RUN 9	11.700	13.300	14.900	16.500	18.100	19.700	21.300	22.900	24.500	26.100	27.700				11	27.70
RUN 10	6.300														1	6.30
RUN 11	4.150	6.150													2	6.15
RUN 12	2.050	3.600													2	3.60
RUN 13	5.200	7.400	42.700												3	42.70
RUN 14	7.150	9.900	11.700	13.900	15.300										5	15.30
RUN 15	2.350	4.000	39.350	39.650											3	39.65
RUN 16	2.300														1	2.30
RUN 17	12.300	14.950	17.600	20.250	22.900	25.550	28.200	30.850	33.500	36.150	38.800	47.150	48.600	50.850	>14	>50.85
RUN 18	7.650	10.000	11.350	12.700	14.050	15.400	16.750	18.100	19.450	20.800	22.150	23.500	24.850	26.200	>14	>26.20
RUN 19	10.250	11.600	12.950	14.300	15.650	17.000	18.350	19.700	21.050	22.400	23.750	25.100	26.450	27.800	>14	>27.80
RUN 20	8.000	10.850	12.650	14.450	16.250	18.050	19.850	21.650	23.450	25.250	27.050	28.850	30.650	32.450	>14	>32.45
RUN 21	NO SOLUTION FOUND - FACTOR OF SAFETY = 825.927														0	0.00
RUN 22	4.550	6.600	8.350												3	8.35
RUN 23	3.050	5.000	6.700												3	6.70
RUN 24	7.900	9.900	11.300	12.700	14.100	15.500	16.900	18.300	19.700	21.100	22.500	23.900	25.300	26.700	>14	>26.70
RUN 25	9.450	11.400	13.350	15.300	40.650	41.800									6	41.80

SECTION 5+70

TABLE A22 SECTION 5+70 HW = 5.0 m

SUMMARY (LOWER LIMIT)
DISTANCE TO CRACK NUMBER

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	TOTAL # CRACKS	EXTENT m
RUN 1	6.870	9.660	11.490	13.320	15.120	16.920	18.720	20.520	22.320	24.120	25.920	27.720	29.520	31.320	20	47.28
RUN 2	5.040	7.620	9.870	11.400	12.930	14.460	15.990	17.520	19.050	20.580	22.110	23.640	25.170	26.700	24	26.92
RUN 3	6.600	9.540	11.520	13.500	15.480	17.460	19.440	21.400	23.490	25.500	27.510	29.520	31.590	33.630	16	37.71
RUN 4	7.650	10.350	12.030	13.710	15.390	17.070	18.750	20.430	22.110	23.790	25.470	27.150	28.830	30.540	21	47.52
RUN 5	9.300	11.790	14.280	16.770	19.260	21.750	24.240	26.730	29.220	31.710	34.200	36.690	39.180	47.010	17	51.42
RUN 6	4.350	6.660	8.670	10.710											4	10.71
RUN 7	3.400	5.640	7.560	9.390											4	9.39
RUN 8	2.490	4.380	5.970	7.530	9.860										5	9.86
RUN 9	14.220	16.920	19.590	22.260	24.930	27.600	30.270	32.900	35.640	38.340					10	38.34
RUN 10	7.770	10.860	12.930	14.970	17.010	19.050	21.090	23.130	25.170	27.210	29.250	31.320	33.390	35.460	15	37.53
RUN 11	5.460	8.010	10.350	11.850	13.380	14.910	16.440	17.970	19.500	21.030	22.560	24.090	25.620	27.150	21	37.89
RUN 12	3.030	5.160	7.050	8.820	10.650	11.910	13.170	14.430	15.690	16.950	18.210	19.470	20.730	21.990	25	43.06
RUN 13	6.630	9.450	11.280	13.110	14.970	16.800	18.630	20.460	22.290	24.120	25.950	27.700	29.610	31.440	18	38.76
RUN 14	8.050	13.110	16.080	19.020	21.990	24.960	27.930	30.930	33.390	36.960					10	36.96
RUN 15	3.420	5.640	7.620	9.480	10.800	12.120	13.440	14.760	16.080	17.400	18.720	20.040	21.360	22.680	23	43.02
RUN 16	3.360	5.610	7.590	9.480	10.800	12.120	13.440	14.760	16.080	17.400	18.720	20.040	21.360		13	21.36
RUN 17	15.600	20.010	24.390	28.770	33.150	37.530									6	37.53
RUN 18	9.030	11.250	13.440	15.630	17.820	20.010	22.200	24.390	26.580	28.770	30.960	33.150	35.340	37.530	17	40.99
RUN 19	12.090	14.310	16.530	18.750	20.970	23.190	25.410	27.630	29.800	32.100	34.320	36.540	38.760	47.310	14	47.31
RUN 20	9.660	12.630	15.600	18.570	21.540	24.510	27.450	30.390	33.330	36.270	39.210				11	39.21
RUN 21	1.290														1	1.29
RUN 22	5.800	8.490	10.920	12.480	14.040	15.600	17.160	18.720	20.280	21.840	23.400	24.990	26.580	28.170	25	49.92
RUN 23	4.290	6.900	9.120	10.650	12.180	13.710	15.240	16.770	18.300	19.830	21.360	22.890	24.450	26.010	22	38.52
RUN 24	8.970	11.280	13.560	15.840	18.120	20.400	22.650	24.930	27.210	29.490	31.770	34.050	36.330	38.610	15	46.74
RUN 25	11.460	14.700	17.910	21.100	24.420	27.660	30.900	34.200	37.470	47.010	48.700	50.500	52.300	54.100	17	59.61
MEAN	7.07	10.00	12.31	14.47	17.00	19.51	20.63	22.65	24.65	27.02	27.69	28.80	30.60	33.73	14.96	36.27
S.D.	3.60	3.95	4.44	5.04	5.70	6.39	5.59	6.17	6.72	8.08	7.94	7.88	8.14	9.25	7.80	14.98
# CASES	25	24	24	24	22	21	20	20	20	20	18	17	17	16	25	25

SECTION 9+70

TABLE A2 3: SECTION 9+70 HW = 0.0 m

SUMMARY (LOWER LIMIT)
DISTANCE TO CRACK NUMBER

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	TOTAL # CRACKS	EXTENT m
RUN 1	11.670	16.950	22.140	27.360	32.500	37.770	47.050	50.190	52.620	55.050	57.540	60.120	61.770	63.420	99	200
RUN 2	9.150	13.470	17.760	22.000	26.370	30.660	34.900	46.110	48.150	50.310	52.500	54.700	57.120	59.490	99	195
RUN 3	11.990	17.190	22.000	28.410	34.000	46.500	49.290	52.140	54.990	57.070	60.010	62.790	64.000	66.040	81	210
RUN 4	12.450	17.310	22.140	26.970	31.000	36.630	47.500	49.560	51.660	53.050	56.070	58.300	60.010	62.250	99	104
RUN 5	17.100	24.450	31.710	38.970	49.230	52.260	55.290	58.320	61.440	63.510	65.900	67.650	69.720	71.790	81	210
RUN 6	8.100	12.700	16.410	20.010	23.610	27.210	30.810	34.410	38.010	46.900	48.630	50.370	52.230	54.150	99	166
RUN 7	7.050	11.290	14.730	18.240	21.720	25.200	28.680	32.160	35.640	39.120	47.100	48.840	50.700	52.650	57	114
RUN 8	5.490	8.940	11.000	14.790	17.700	20.640	23.950	26.490	29.430	32.370	35.310	38.250	46.110	47.900	99	161
RUN 9	33.630	40.690	51.330	54.000	56.700	59.400	61.110	62.790	64.470	66.150	67.830	69.510	71.190	72.870	95	210
RUN 10	13.290	19.230	25.000	30.960	36.040	47.000	50.950	53.250	55.900	58.710	60.540	62.370	64.200	66.060	98	210
RUN 11	9.570	13.090	18.100	22.500	26.790	31.110	35.430	46.440	48.420	50.520	52.710	54.930	57.240	59.640	99	194
RUN 12	6.400	10.560	14.040	17.520	21.030	24.510	27.990	31.470	34.950	38.460	46.590	48.400	50.430	52.500	99	106
RUN 13	11.370	16.620	21.010	27.000	32.220	37.440	47.760	50.100	52.590	55.140	57.690	60.330	62.040	63.750	98	210
RUN 14	16.740	25.230	33.660	47.640	51.630	55.470	59.160	61.890	64.620	67.350	70.110	72.870	75.630	78.390	59	210
RUN 15	7.000	11.430	15.120	18.700	22.440	26.100	29.760	33.420	37.110	46.200	48.090	50.100	52.200	54.330	99	107
RUN 16	7.050	11.430	15.100	18.870	22.560	26.250	29.940	33.630	37.320	46.260	48.100	50.220	52.290	54.450	99	106
RUN 17	49.030	54.100	58.260	62.400	65.250	68.100	70.950	73.800	76.650	79.500	82.350	85.200	88.050	90.900	57	210
RUN 18	16.020	22.530	28.900	35.460	47.000	50.520	53.220	55.950	58.650	60.400	62.200	64.000	65.800	67.600	93	210
RUN 19	24.400	31.440	38.250	49.230	51.510	53.050	56.200	58.770	60.270	61.770	63.270	64.770	66.270	67.770	99	195
RUN 20	10.700	27.510	36.150	40.720	52.410	55.950	59.400	61.890	64.350	66.810	69.270	71.730	74.190	76.620	69	210
RUN 21	3.150	5.790	8.130	10.410	12.400	14.500	16.600	18.700	20.910	23.010	25.110	27.210	29.310	31.410	27	56.9
RUN 22	10.000	14.950	18.990	23.430	27.900	32.370	36.840	47.130	49.170	51.330	53.900	55.060	58.200	60.660	99	195
RUN 23	8.430	13.950	18.270	22.990	26.910	31.230	35.550	46.020	48.210	50.920	52.030	55.230	57.630	60.190	99	203
RUN 24	16.050	22.000	29.490	36.100	40.120	50.940	53.760	56.500	59.370	61.290	63.100	65.070	66.960	68.820	92	210
RUN 25	23.020	33.560	40.400	52.260	55.090	59.430	61.090	64.300	66.070	69.360	71.000	74.370	76.060	79.350	65	210
MEAN	14.34	20.23	25.56	30.99	35.03	40.00	44.17	48.23	50.87	54.00	56.76	58.94	61.27	63.34	86.00	189.72
S.D.	10.12	11.71	12.05	14.11	14.50	14.53	14.26	13.95	13.33	12.53	12.07	12.13	11.00	12.01	19.37	35.20
# CASES	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25

Table A24

Probability of Cracking Extending Beyond Xi Metres

Section 5+ 70 - H_w Variation

(25 runs each case)

	Hw=1.5m		Hw= 2.0m		Hw= 3.0m		Hw= 4.0m		Hw= 5.0m		Hw= 7.0m		Hw= 8.0m	
Xi - m	#	%	#	%	#	%	#	%	#	%	#	%	#	%
0	3	12	8	32	17	68	22	88	25	100	25	100	25	100
1	1	4	6	24	-	-	-	-	-	-	-	-	-	-
2	0	0	5	20	-	-	-	-	-	-	-	-	-	-
3	-	-	5	20	15	60	-	-	-	-	-	-	-	-
4	-	-	3	12	-	-	-	-	-	-	-	-	-	-
5	-	-	3	12	12	48	19	76	24	96	-	-	-	-
6	-	-	2	8	9	36	-	-	-	-	-	-	-	-
7	-	-	2	8	-	-	14	56	-	-	-	-	-	-
8	-	-	2	8	5	20	-	-	-	-	-	-	-	-
9	-	-	0	0	-	-	-	-	-	-	-	-	-	-
10	-	-	-	-	4	16	10	40	22	88	-	-	-	-
20	-	-	-	-	2	8	9	36	21	84			25	100
30	-	-	-	-	2	8	7	28	19	76	25	100	25	100
40	-	-	-	-	1	4	3	12	10	40	22	88	25	100
50	-	-	-	-	-	-	1	4	2	8	22	88	25	100
60	-	-	-	-	-	-	-	-	0	0	13	52	24	96
70	-	-	-	-	-	-	-	-	-	-	10	40	-	-
80	-	-	-	-	-	-	-	-	-	-	10	40	-	-
90	-	-	-	-	-	-	-	-	-	-	9	36	-	-
100	-	-	-	-	-	-	-	-	-	-	8	32	-	-
125	-	-	-	-	-	-	-	-	-	-	8	32	23	92
150	-	-	-	-	-	-	-	-	-	-	6	24	-	-
175	-	-	-	-	-	-	-	-	-		6	24	23	92

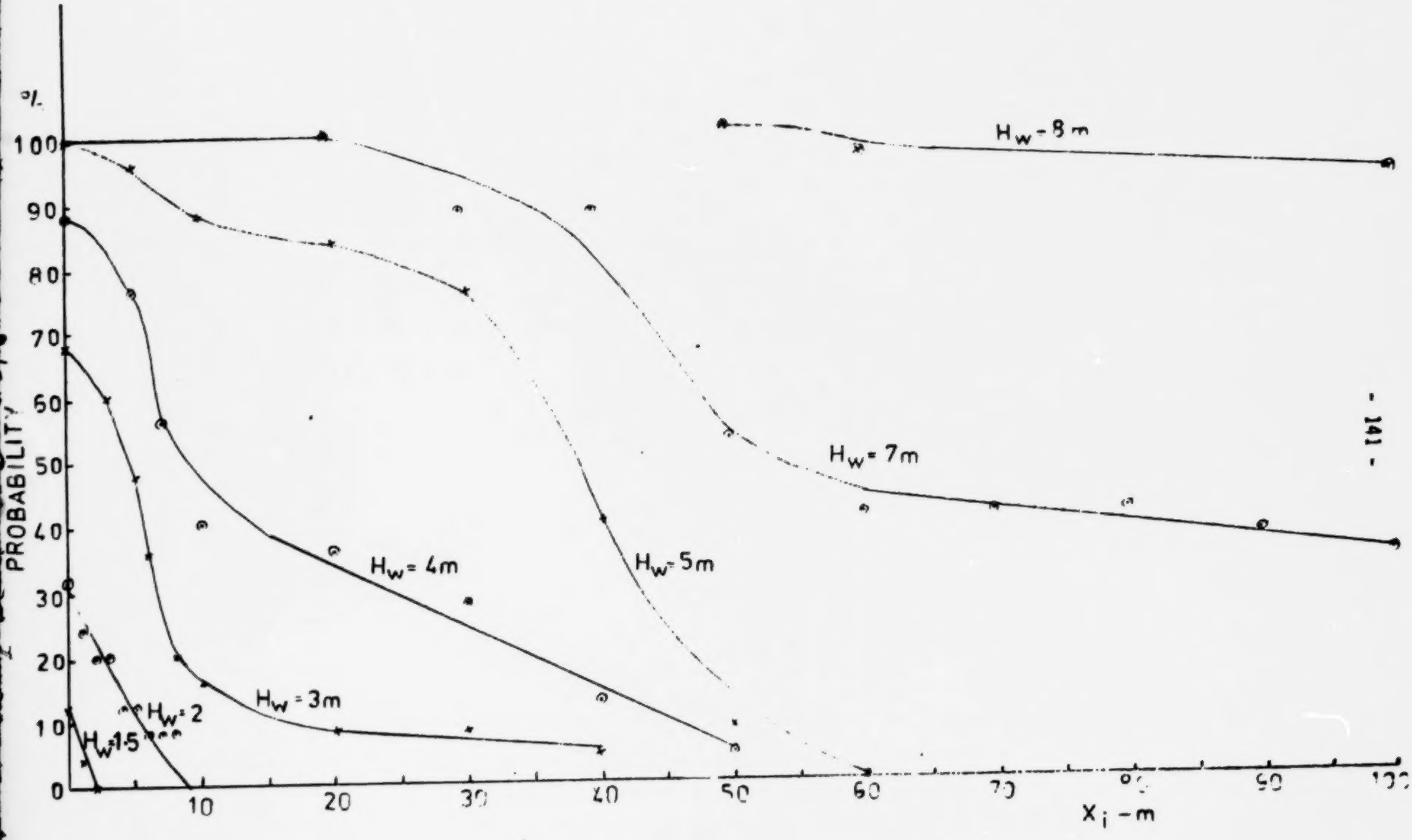


FIG A5.3 : PROBILITY OF CRACKING BEYOND X_i METRES - H_w VARIED - SECTION 5+70

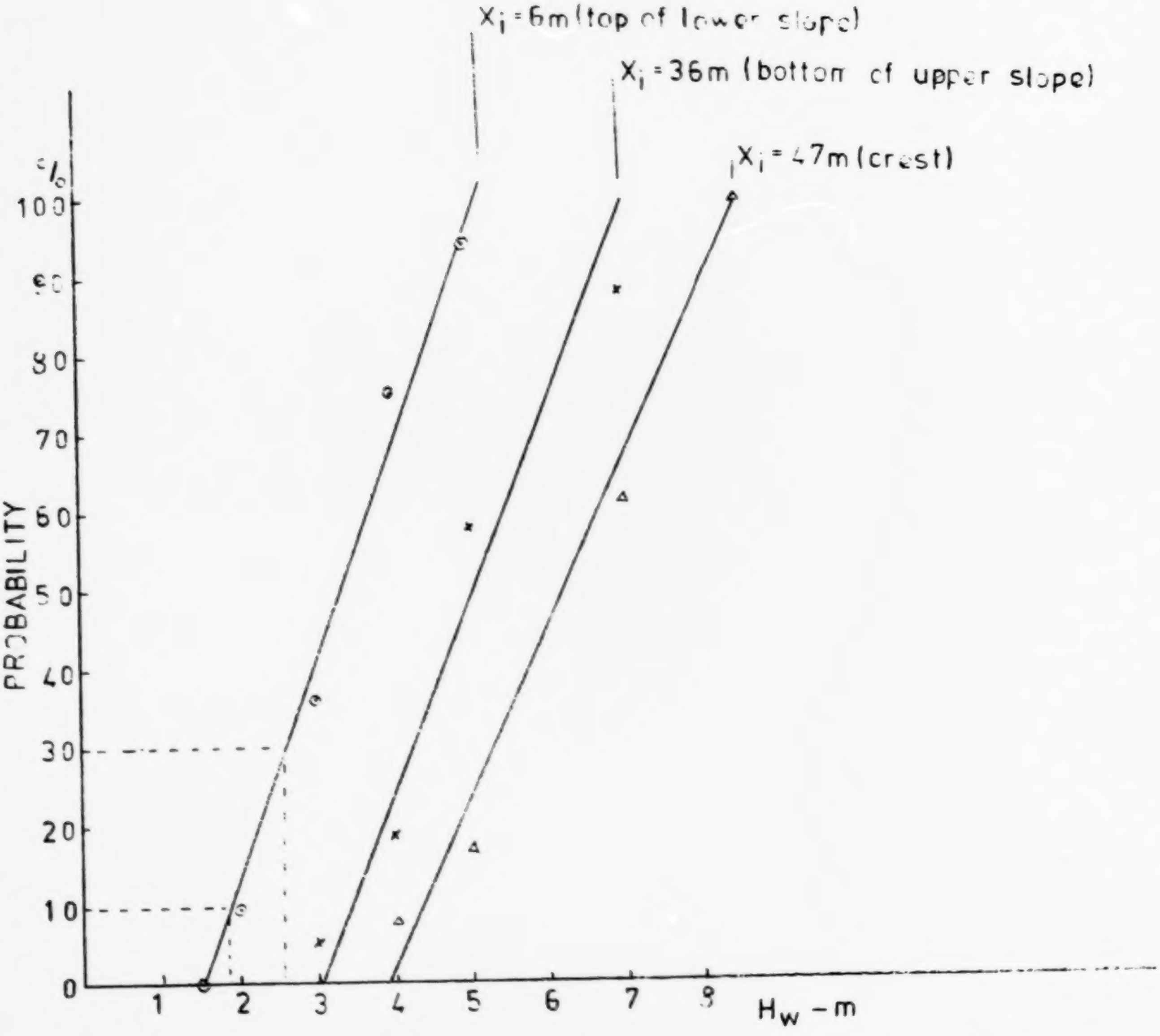


FIG A5·4 : PROBABILITY OF FAILURE EXTENDING BEYOND SPECIFIC DISTANCES VERSUS H_w - SECTION 5+70

Effect of increasing the depth of mining

As mining gets deeper the effect on stability will depend on a number of factors.

(1) If we assume that the failure plane (bentonitic clay band) remains a constant distance above the coal seam, then the failure plane will also get deeper.

(2) The stability will then depend on what happens to the water table. If the water table height above the failure plane remains constant (i.e. the depth below surface increases) then the stability of the slope will also increase since the resisting force due to friction is proportional to the normal force. Thus as the weight of overburden material increases with depth, so the resisting force will increase and the slope will become more stable.

(3) However, it would seem unlikely that the water table would remain a constant height above the failure plane as depth increases. A more likely circumstance would be that the water table remains a constant depth below surface. In this case the stability of the slope will increase or decrease depending whether the rate of increase of resisting force is less than or greater than the rate of increase of uplift force due to the water pressure increase. A complete analysis should be carried out for each particular circumstance in this case.

FIGURE

PROGRAM LOGIC

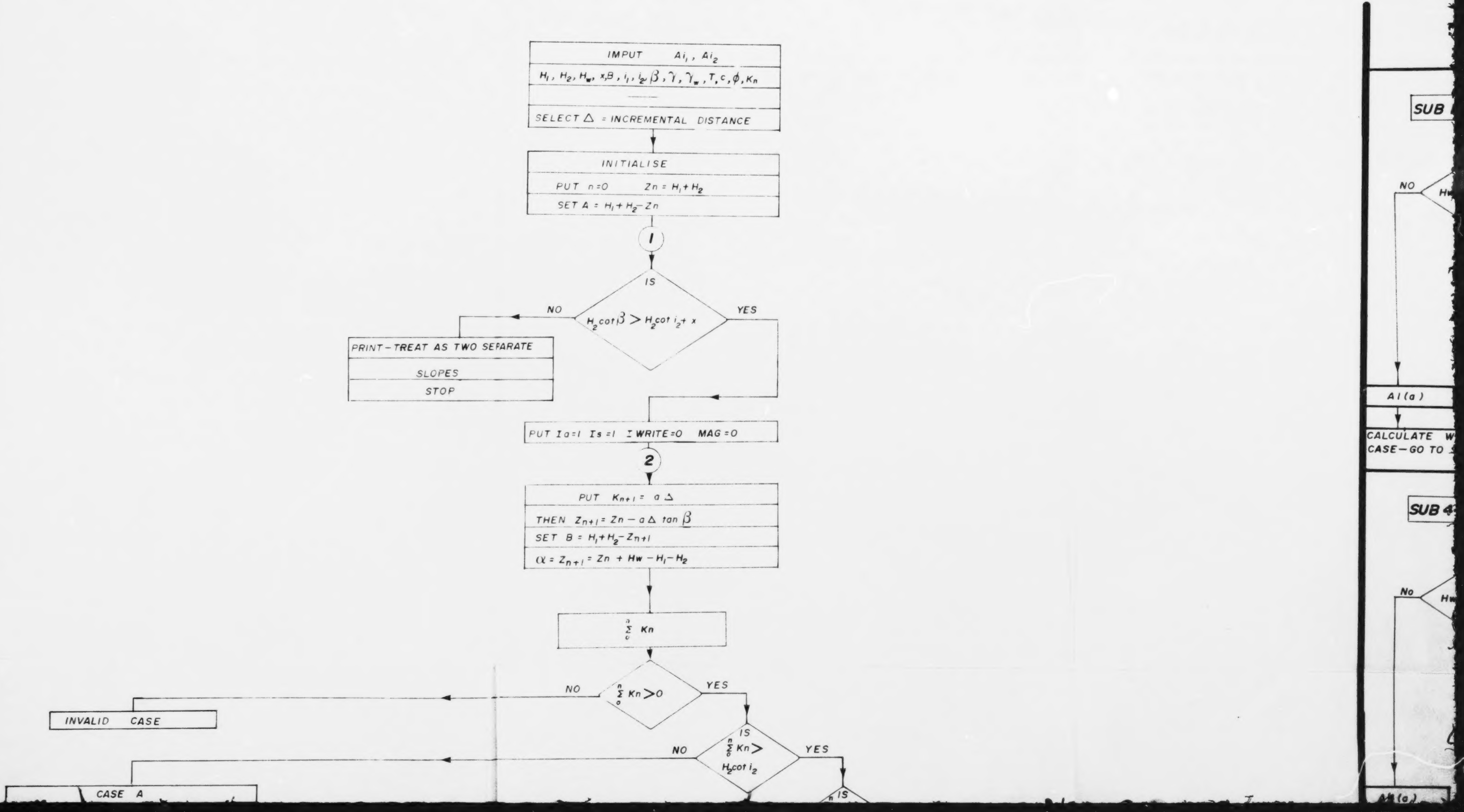
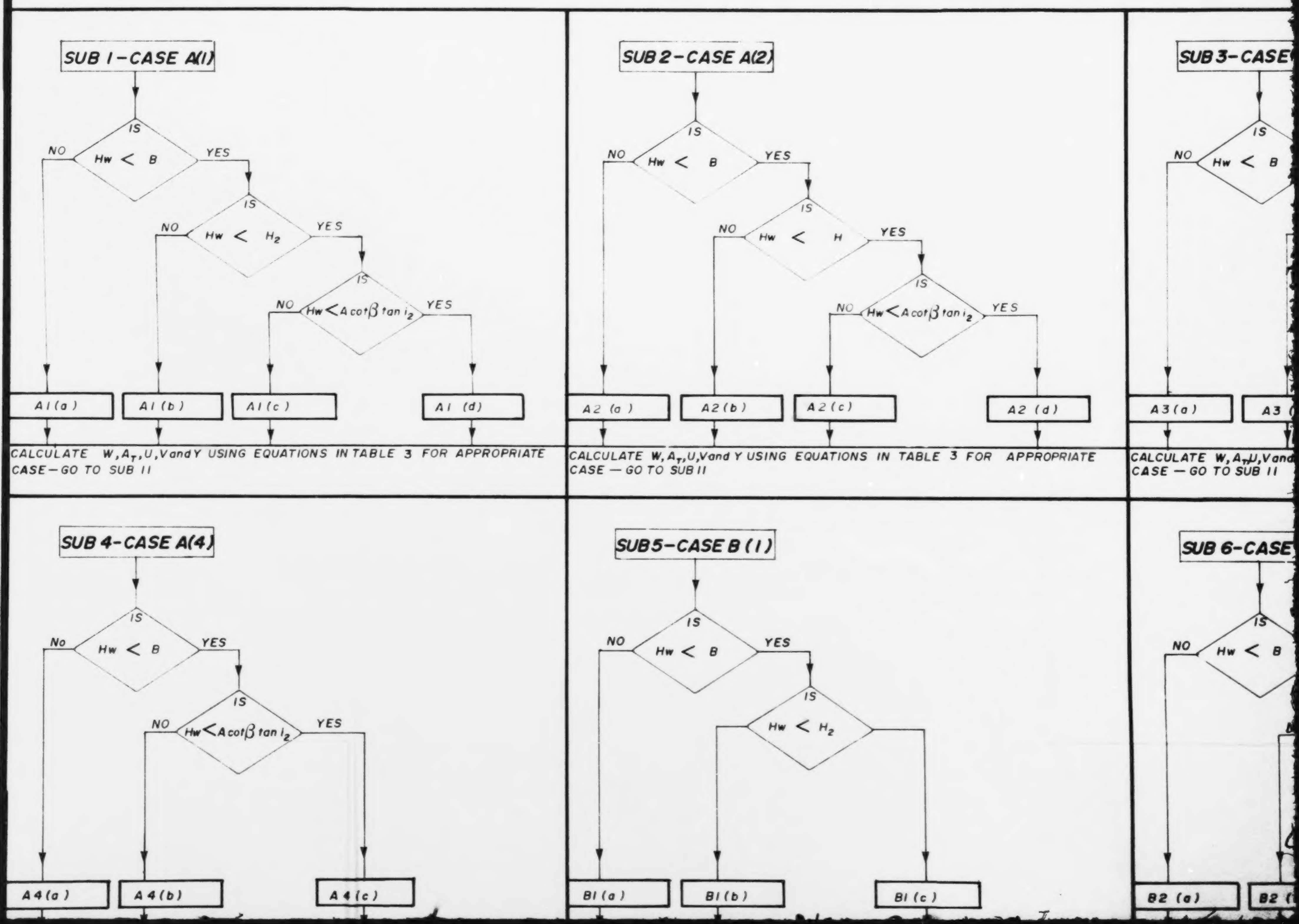

IMPUT Ai_1, Ai_2
H_1, H_2, H_w, x, B, i_1, i_2, β, γ, γ_w, T, c, ϕ, K_n
SELECT Δ = INCREMENTAL DISTANCE
INITIALISE
PUT $n=0$ $Zn = H_1 + H_2$
SET $A = H_1 + H_2 - Zn$
1
IS
$H_2 \cot\beta > H_2 \cot i_2 + x$
NO
YES
PRINT - TREAT AS TWO SEPARATE
SLOPES
STOP
PUT $Ia=1$ $Is=1$ I WRITE$=0$ MAG$=0$
2
PUT $K_{n+1} = a\Delta$
THEN $Z_{n+1} = Zn - a\Delta \tan\beta$
SET $B = H_1 + H_2 - Z_{n+1}$
$\alpha = Z_{n+1} = Zn + Hw - H_1 - H_2$
$\sum_0^n Kn$
NO
$\sum_0^n Kn > 0$
YES
INVALID CASE
IS
$\sum_0^n Kn >$
$H_2 \cot i_2$
NO
YES
CASE A
IS
SUB
NO
Hw
AI(a)
CALCULATE W
CASE—GO TO
SUB 4
No
Hw
AI(a)

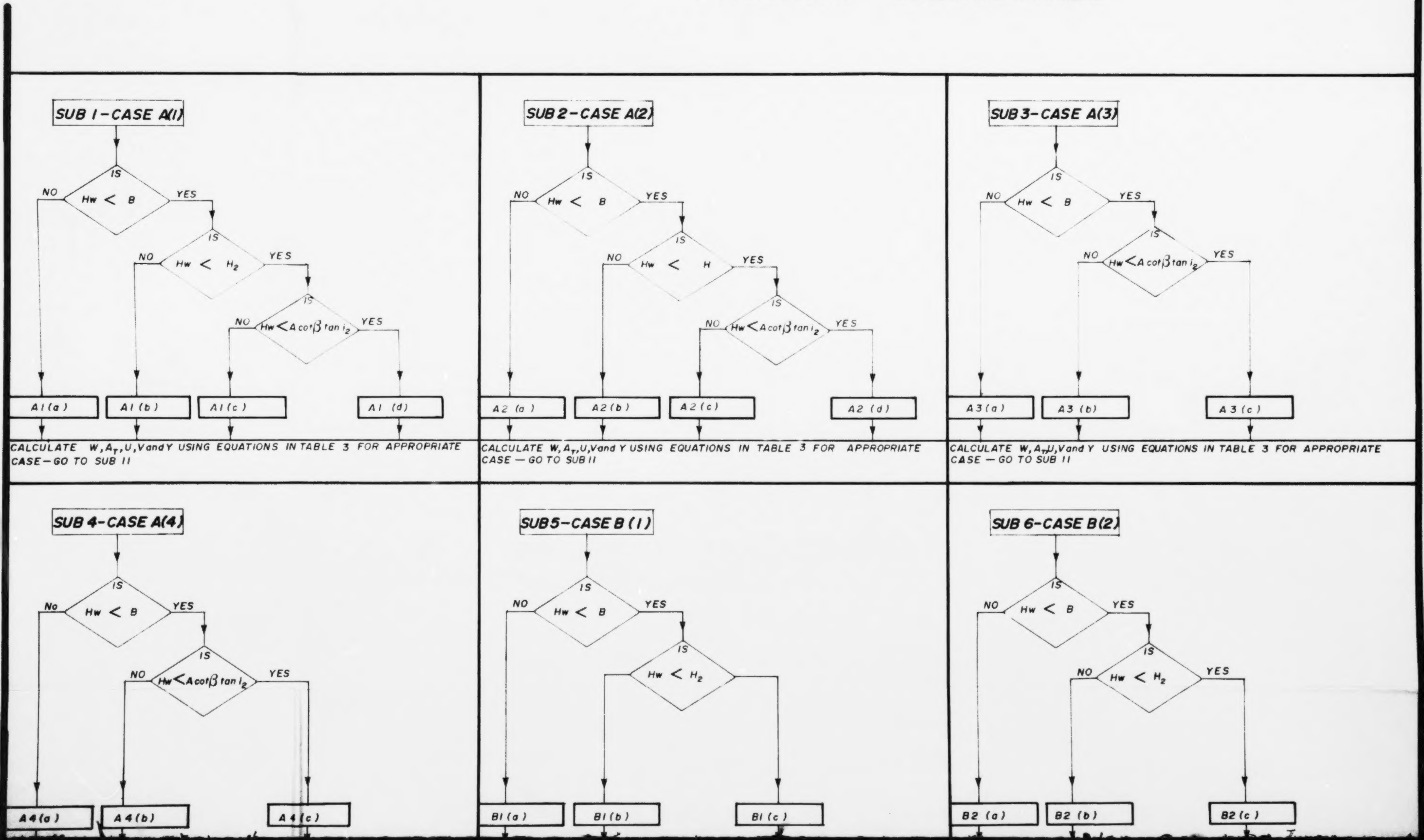
FIGURE 13

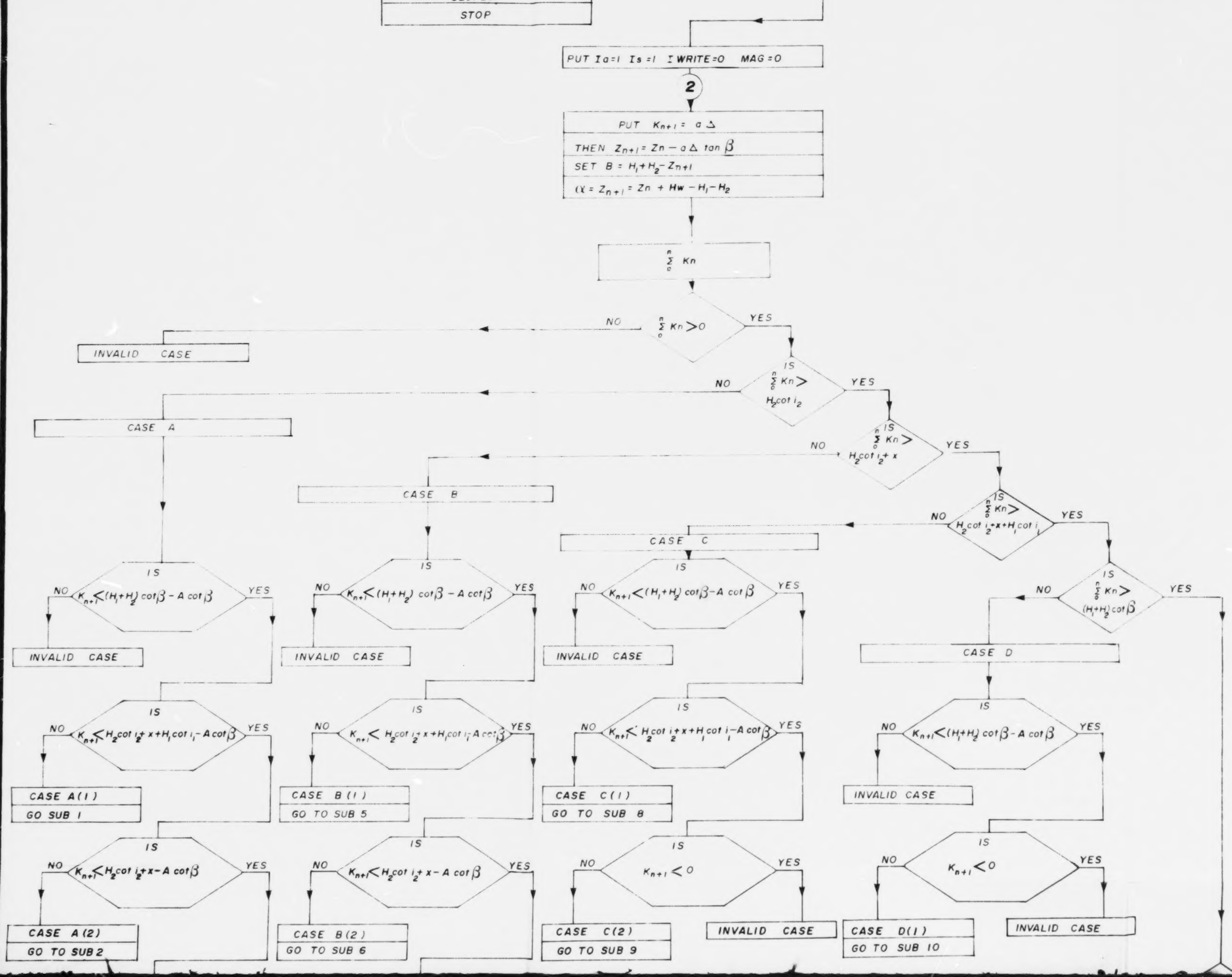
PROGRAM SUBROUTINE

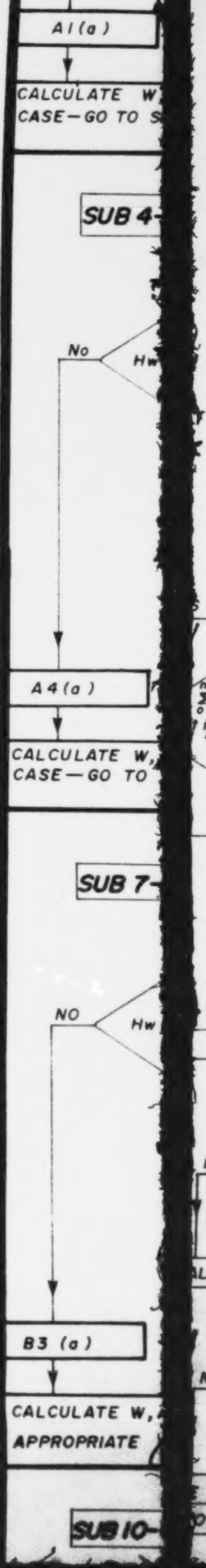

SUB 1-CASE A(1)
IS
Hw < B
NO
YES
IS
Hw < H_2
NO
YES
IS
Hw < A cot β tan i_2
NO
YES
A1(a)
A1(b)
A1(c)
A1(d)
CALCULATE W, A_T, U, V and Y USING EQUATIONS IN TABLE 3 FOR APPROPRIATE CASE—GO TO SUB 11
SUB 2-CASE A(2)
IS
Hw < B
NO
YES
IS
Hw < H
NO
YES
IS
Hw < A cot β tan i_2
NO
YES
A2(a)
A2(b)
A2(c)
A2(d)
CALCULATE W, A_T, U, V and Y USING EQUATIONS IN TABLE 3 FOR APPROPRIATE CASE — GO TO SUB 11
SUB 3-CASE
IS
Hw < B
NO
A3(a)
A3
CALCULATE W, A_T, U, V and
CASE — GO TO SUB 11
SUB 4-CASE A(4)
IS
Hw < B
No
YES
IS
Hw < A cot β tan i_2
NO
YES
A4(a)
A4(b)
A4(c)
SUB 5-CASE B(1)
IS
Hw < B
NO
YES
IS
Hw < H_2
B1(a)
B1(b)
B1(c)
SUB 6-CASE
IS
Hw < B
NO
B2(a)
B2

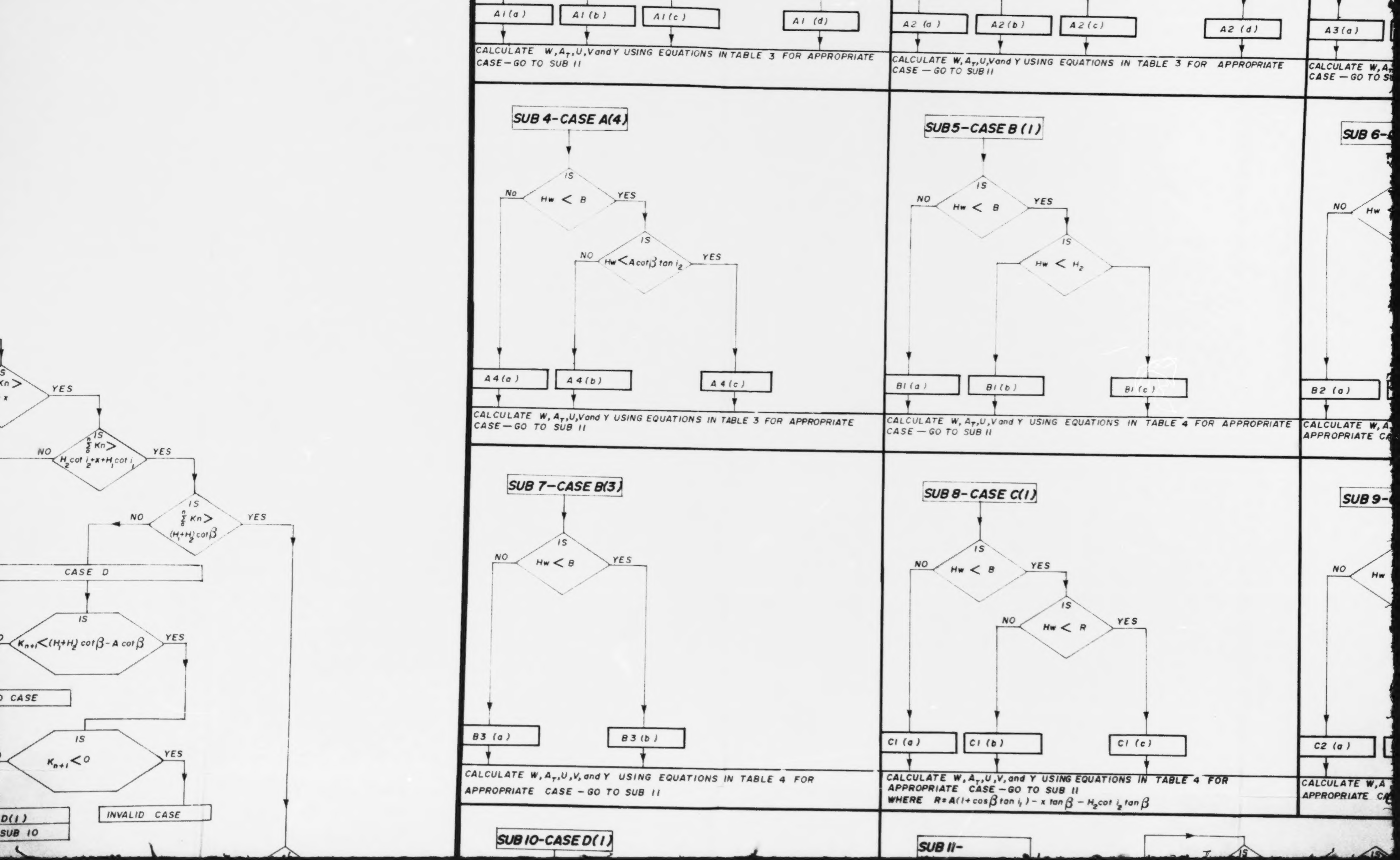
GURE 13

PROGRAM SUBROUTINES

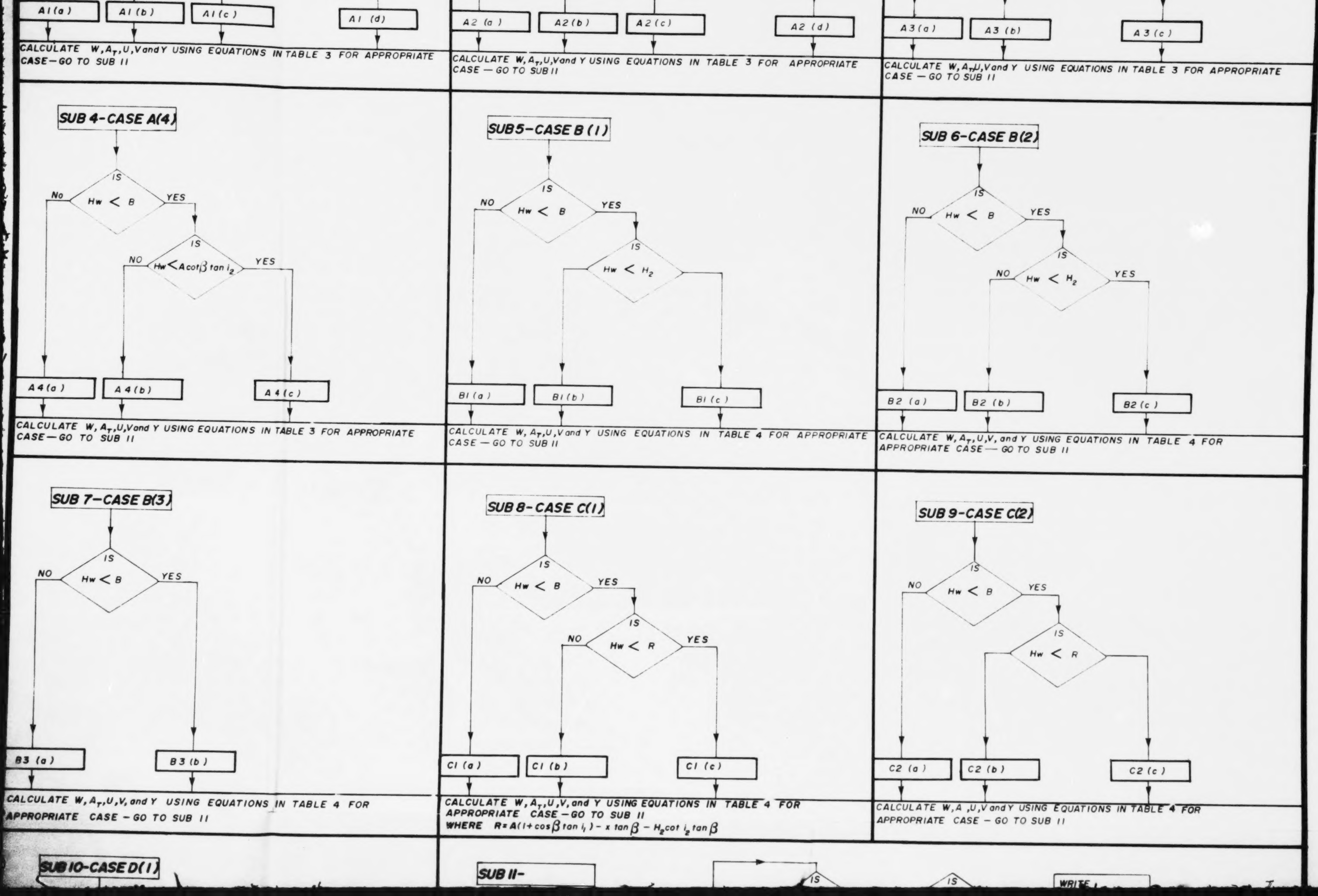

SUB 1-CASE A(1)
IS Hw < B
NO
YES
IS Hw < H_2
IS Hw < A cot β tan i_2
A1 (a)
A1 (b)
A1 (c)
A1 (d)
CALCULATE W, A_T, U, V and Y USING EQUATIONS IN TABLE 3 FOR APPROPRIATE CASE—GO TO SUB 11
SUB 2-CASE A(2)
IS Hw < B
IS Hw < H
IS Hw < A cot β tan i_2
A2 (a)
A2 (b)
A2 (c)
A2 (d)
CALCULATE W, A_T, U, V and Y USING EQUATIONS IN TABLE 3 FOR APPROPRIATE CASE — GO TO SUB 11
SUB 3-CASE A(3)
IS Hw < B
IS Hw < A cot β tan i_2
A3 (a)
A3 (b)
A3 (c)
CALCULATE W, A_T, U, V and Y USING EQUATIONS IN TABLE 3 FOR APPROPRIATE CASE — GO TO SUB 11
SUB 4-CASE A(4)
IS Hw < B
No
IS Hw < A cot β tan i_2
A4 (a)
A4 (b)
A4 (c)
SUB 5-CASE B (1)
IS Hw < B
IS Hw < H_2
B1 (a)
B1 (b)
B1 (c)
SUB 6-CASE B (2)
IS Hw < B
IS Hw < H_2
B2 (a)
B2 (b)
B2 (c)

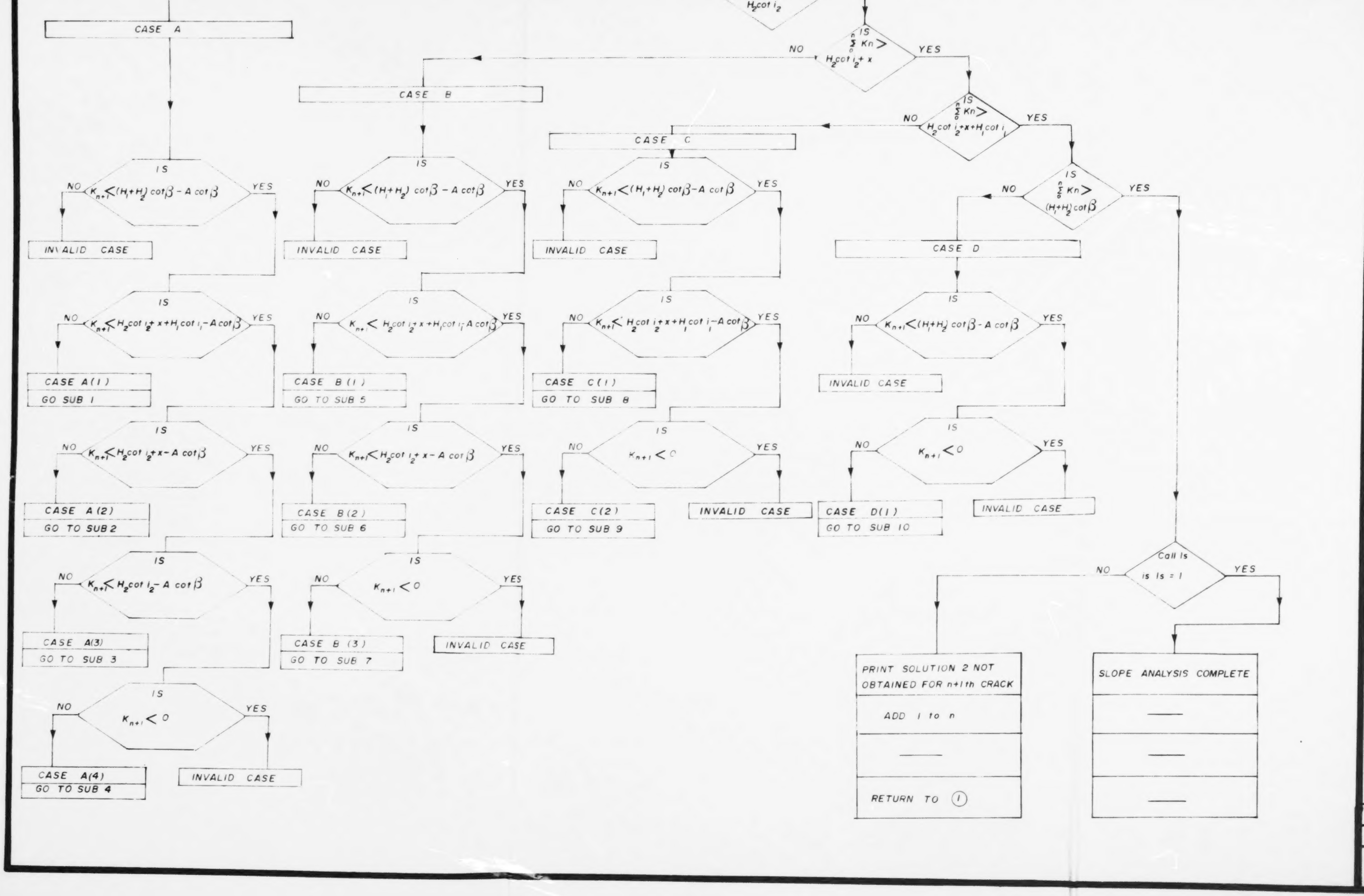

STOP
PUT Ia=1 Is=1 I WRITE=0 MAG=0
2
PUT $K_{n+1} = a\Delta$
THEN $Z_{n+1} = Zn - a\Delta \tan\beta$
SET $B = H_1+H_2-Z_{n+1}$
$\alpha = Z_{n+1} = Zn + Hw - H_1 - H_2$
$\sum_0^n Kn$
$\sum_0^n Kn > 0$
NO
YES
INVALID CASE
IS $\sum_0^n Kn > H_2 \cot i_2$
NO
YES
CASE A
IS $\sum_0^n Kn > H_2 \cot i_2 + x$
NO
YES
CASE B
IS $\sum_0^n Kn > H_2 \cot i_2 + x + H_1 \cot i_1$
NO
YES
CASE C
IS $\sum_0^n Kn > (H_1+H_2)\cot\beta$
NO
YES
CASE D
IS $K_{n+1} < (H_1+H_2)\cot\beta - A\cot\beta$
NO
YES
INVALID CASE
IS $K_{n+1} < (H_1+H_2)\cot\beta - A\cot\beta$
NO
YES
INVALID CASE
IS $K_{n+1} < (H_1+H_2)\cot\beta - A\cot\beta$
NO
YES
INVALID CASE
IS $K_{n+1} < H_2\cot i_2 + x + H_1\cot i_1 - A\cot\beta$
NO
YES
CASE A(1)
GO SUB 1
IS $K_{n+1} < H_2\cot i_2 + x + H_1\cot i_1 - A\cot\beta$
NO
YES
CASE B(1)
GO TO SUB 5
IS $K_{n+1} < H_2\cot i_2 + x + H_1\cot i_1 - A\cot\beta$
NO
YES
CASE C(1)
GO TO SUB 8
IS $K_{n+1} < (H_1+H_2)\cot\beta - A\cot\beta$
NO
YES
INVALID CASE
IS $K_{n+1} < H_2\cot i_2 + x - A\cot\beta$
NO
YES
CASE A(2)
GO TO SUB 2
IS $K_{n+1} < H_2\cot i_2 + x - A\cot\beta$
NO
YES
CASE B(2)
GO TO SUB 6
IS $K_{n+1} < 0$
NO
YES
CASE C(2)
GO TO SUB 9
INVALID CASE
IS $K_{n+1} < 0$
NO
YES
CASE D(1)
GO TO SUB 10
INVALID CASE


A1(a)
CALCULATE W
CASE—GO TO S
SUB 4
No
Hw
A4(a)
CALCULATE W,
CASE—GO TO
SUB 7
NO
Hw
B3 (a)
CALCULATE W,
APPROPRIATE
SUB 10

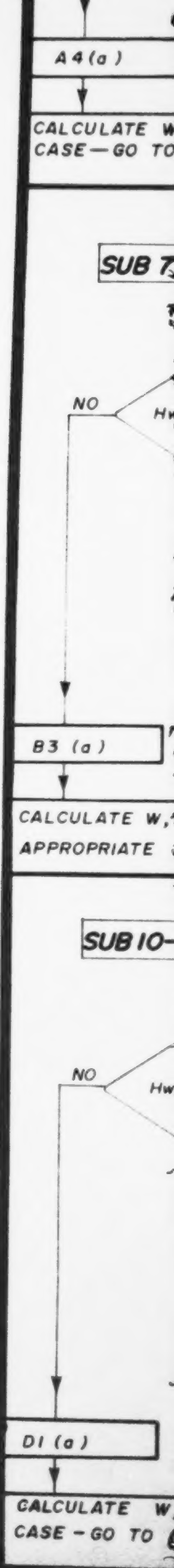


A1 (a)
A1 (b)
A1 (c)
A1 (d)
CALCULATE W, A_T, U, V and Y USING EQUATIONS IN TABLE 3 FOR APPROPRIATE CASE – GO TO SUB 11
A2 (a)
A2 (b)
A2 (c)
A2 (d)
CALCULATE W, A_T, U, V and Y USING EQUATIONS IN TABLE 3 FOR APPROPRIATE CASE – GO TO SUB 11
A3 (a)
CALCULATE W, A_T
CASE – GO TO S
SUB 4 – CASE A(4)
IS $H_w < B$
NO
YES
IS $H_w < A \cot\beta \tan i_2$
NO
YES
A4 (a)
A4 (b)
A4 (c)
CALCULATE W, A_T, U, V and Y USING EQUATIONS IN TABLE 3 FOR APPROPRIATE CASE – GO TO SUB 11
SUB 5 – CASE B (1)
IS $H_w < B$
NO
YES
IS $H_w < H_2$
B1 (a)
B1 (b)
B1 (c)
CALCULATE W, A_T, U, V and Y USING EQUATIONS IN TABLE 4 FOR APPROPRIATE CASE – GO TO SUB 11
SUB 6 –
NO
Hw
B2 (a)
CALCULATE W, A
APPROPRIATE CA
IS $\sum_0^n K_n >$ ... x
YES
IS $\sum_0^n K_n > H_2 \cot i_2 + x + H_1 \cot i_1$
NO
YES
IS $\sum_0^n K_n > (H_1 + H_2) \cot\beta$
NO
YES
CASE D
IS $K_{n+1} < (H_1 + H_2) \cot\beta - A \cot\beta$
YES
CASE
IS $K_{n+1} < 0$
YES
D(1)
SUB 10
INVALID CASE
SUB 7 – CASE B(3)
IS $H_w < B$
NO
YES
B3 (a)
B3 (b)
CALCULATE W, A_T, U, V, and Y USING EQUATIONS IN TABLE 4 FOR APPROPRIATE CASE – GO TO SUB 11
SUB 8 – CASE C(1)
IS $H_w < B$
NO
YES
IS $H_w < R$
NO
YES
C1 (a)
C1 (b)
C1 (c)
CALCULATE W, A_T, U, V, and Y USING EQUATIONS IN TABLE 4 FOR APPROPRIATE CASE – GO TO SUB 11
WHERE $R = A(1 + \cos\beta \tan i_1) - x \tan\beta - H_2 \cot i_2 \tan\beta$
SUB 9 –
NO
Hw
C2 (a)
CALCULATE W, A
APPROPRIATE CA
SUB 10 – CASE D(1)
SUB 11 –
IS

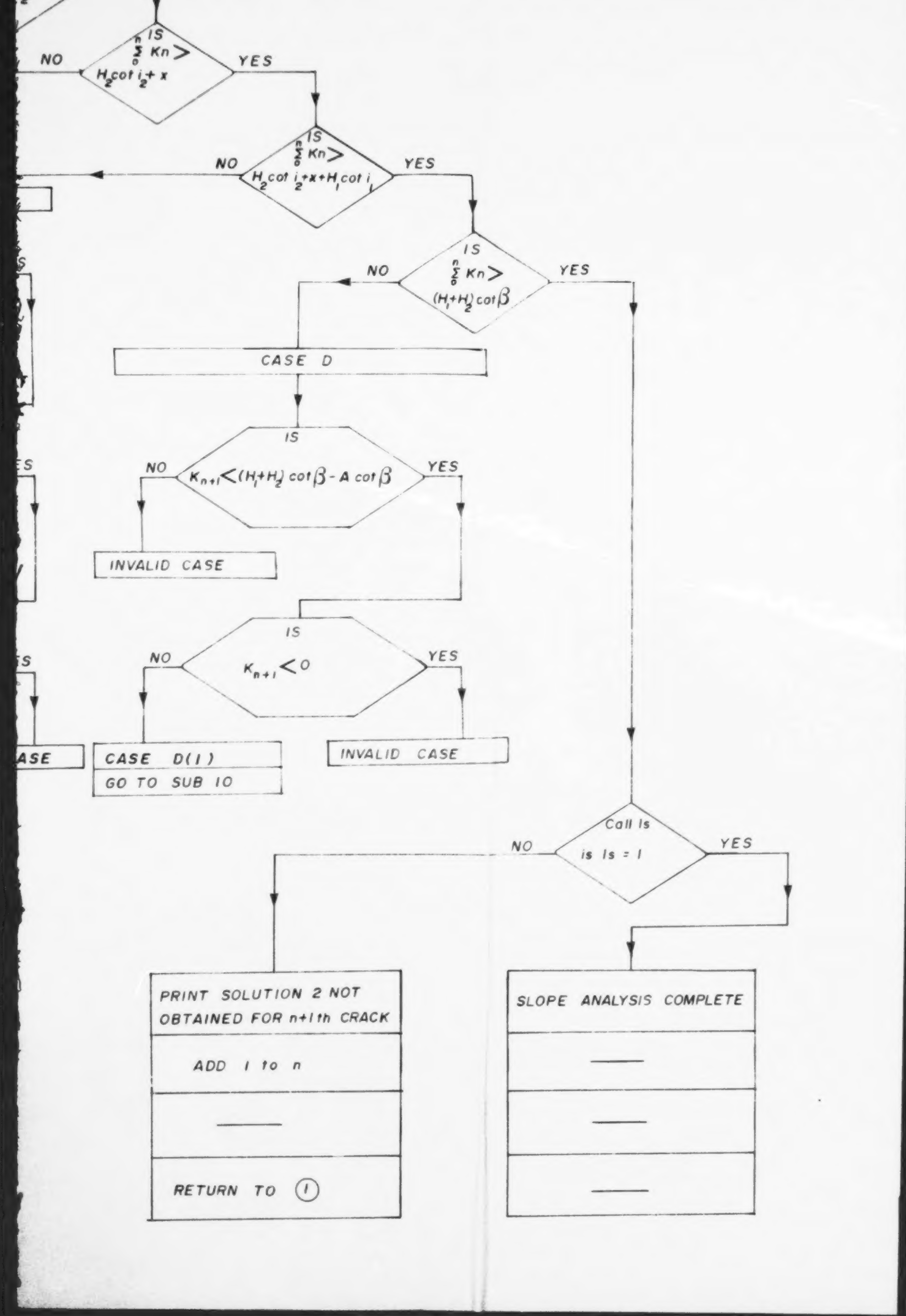

A1(a)
A1(b)
A1(c)
A1 (d)
CALCULATE W, A_T, U, V and Y USING EQUATIONS IN TABLE 3 FOR APPROPRIATE CASE—GO TO SUB 11
A2 (a)
A2(b)
A2(c)
A2 (d)
CALCULATE W, A_T, U, V and Y USING EQUATIONS IN TABLE 3 FOR APPROPRIATE CASE — GO TO SUB 11
A3(a)
A3 (b)
A3 (c)
CALCULATE W, A_T, U, V and Y USING EQUATIONS IN TABLE 3 FOR APPROPRIATE CASE — GO TO SUB 11
SUB 4-CASE A(4)
IS
Hw < B
No
YES
IS
Hw < A cot β tan i_2
NO
YES
A4(a)
A4(b)
A4(c)
CALCULATE W, A_T, U, V and Y USING EQUATIONS IN TABLE 3 FOR APPROPRIATE CASE—GO TO SUB 11
SUB5-CASE B(1)
IS
Hw < B
NO
YES
IS
Hw < H_2
B1(a)
B1(b)
B1(c)
CALCULATE W, A_T, U, V and Y USING EQUATIONS IN TABLE 4 FOR APPROPRIATE CASE — GO TO SUB 11
SUB 6-CASE B(2)
IS
Hw < B
NO
YES
IS
Hw < H_2
NO
YES
B2 (a)
B2 (b)
B2 (c)
CALCULATE W, A_T, U, V, and Y USING EQUATIONS IN TABLE 4 FOR APPROPRIATE CASE — GO TO SUB 11
SUB 7-CASE B(3)
IS
Hw < B
NO
YES
B3 (a)
B3 (b)
CALCULATE W, A_T, U, V, and Y USING EQUATIONS IN TABLE 4 FOR APPROPRIATE CASE - GO TO SUB 11
SUB 8-CASE C(1)
IS
Hw < B
NO
YES
IS
Hw < R
NO
YES
C1 (a)
C1 (b)
C1 (c)
CALCULATE W, A_T, U, V, and Y USING EQUATIONS IN TABLE 4 FOR APPROPRIATE CASE — GO TO SUB 11
WHERE $R = A(1+\cos\beta \tan i_1) - x \tan\beta - H_2 \cot i_2 \tan\beta$
SUB 9-CASE C(2)
IS
Hw < B
NO
YES
IS
Hw < R
C2 (a)
C2 (b)
C2 (c)
CALCULATE W, A, U, V and Y USING EQUATIONS IN TABLE 4 FOR APPROPRIATE CASE - GO TO SUB 11
SUB 10-CASE D(1)
SUB 11-
IS
IS
WRITE

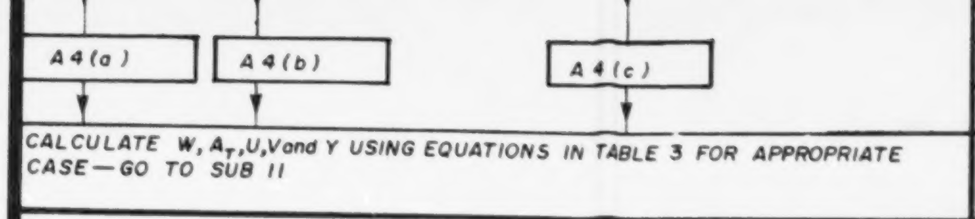


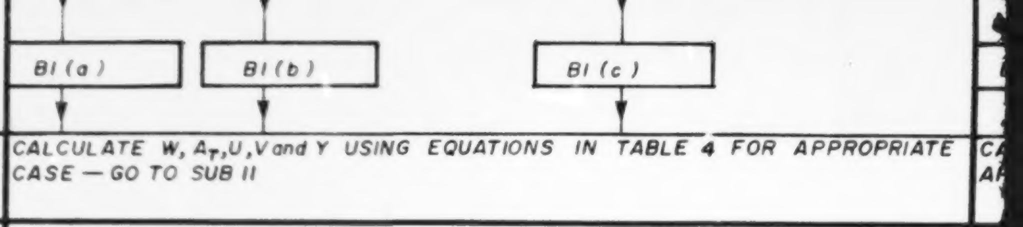
$H_2 \cot i_2$
IS $\sum_0^n K_n > H_2 \cot i_2 + x$
NO
YES
CASE A
CASE B
IS $\sum_0^n K_n > H_2 \cot i_2 + x + H_1 \cot i_1$
NO
YES
CASE C
IS $\sum_0^n K_n > (H_1+H_2) \cot \beta$
NO
YES
CASE D
IS $K_{n+1} < (H_1+H_2) \cot \beta - A \cot \beta$
INVALID CASE
IS $K_{n+1} < H_2 \cot i_2 + x + H_1 \cot i_1 - A \cot \beta$
CASE A(1)
GO SUB 1
CASE B(1)
GO TO SUB 5
CASE C(1)
GO TO SUB 8
IS $K_{n+1} < H_2 \cot i_2 + x - A \cot \beta$
CASE A(2)
GO TO SUB 2
CASE B(2)
GO TO SUB 6
IS $K_{n+1} < 0$
CASE C(2)
GO TO SUB 9
CASE D(1)
GO TO SUB 10
IS $K_{n+1} < H_2 \cot i_2 - A \cot \beta$
CASE A(3)
GO TO SUB 3
CASE B (3)
GO TO SUB 7
CASE A(4)
GO TO SUB 4
Call Is
is Is = 1
PRINT SOLUTION 2 NOT OBTAINED FOR n+1th CRACK
ADD 1 to n
RETURN TO ①
SLOPE ANALYSIS COMPLETE

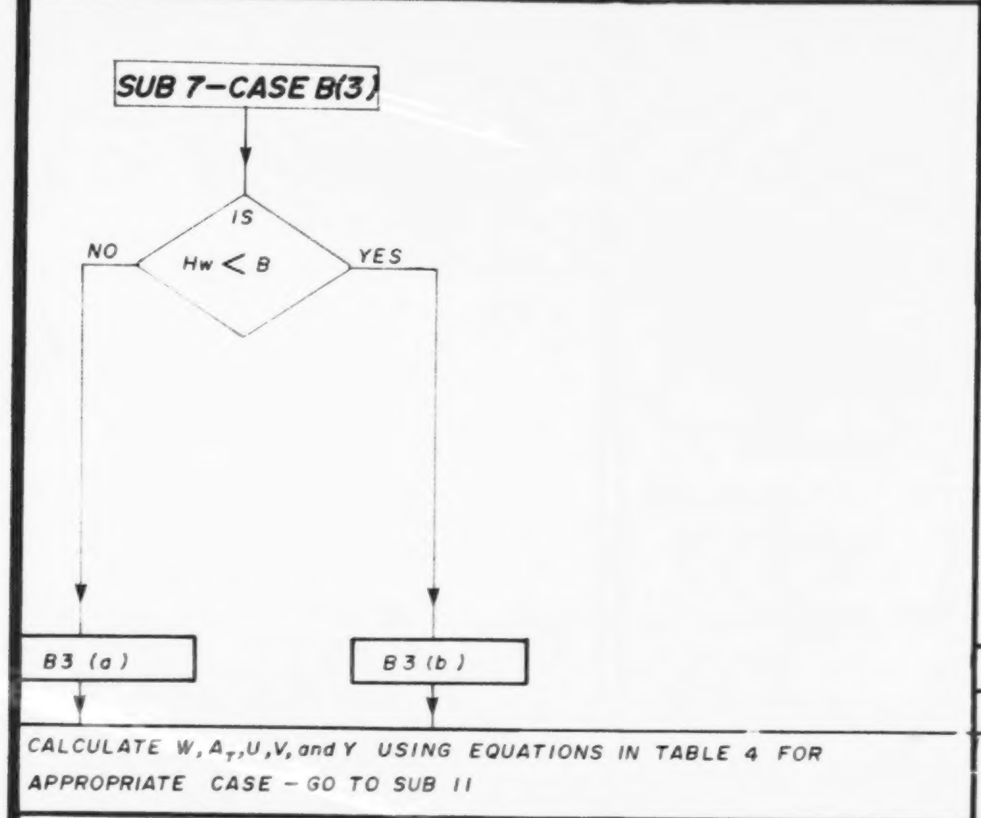


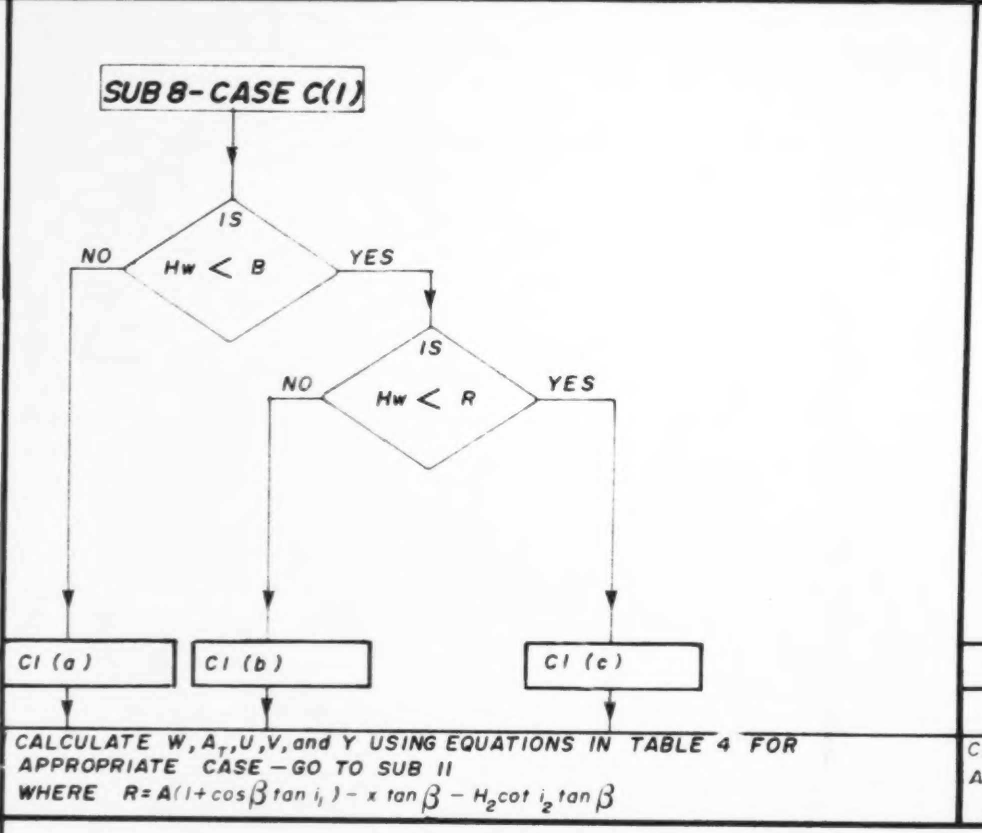
A4(a)
CALCULATE W
CASE—GO TO
SUB 7
NO
Hw
B3 (a)
CALCULATE W,
APPROPRIATE
SUB 10—
NO
Hw
D1 (a)
CALCULATE W,
CASE - GO TO

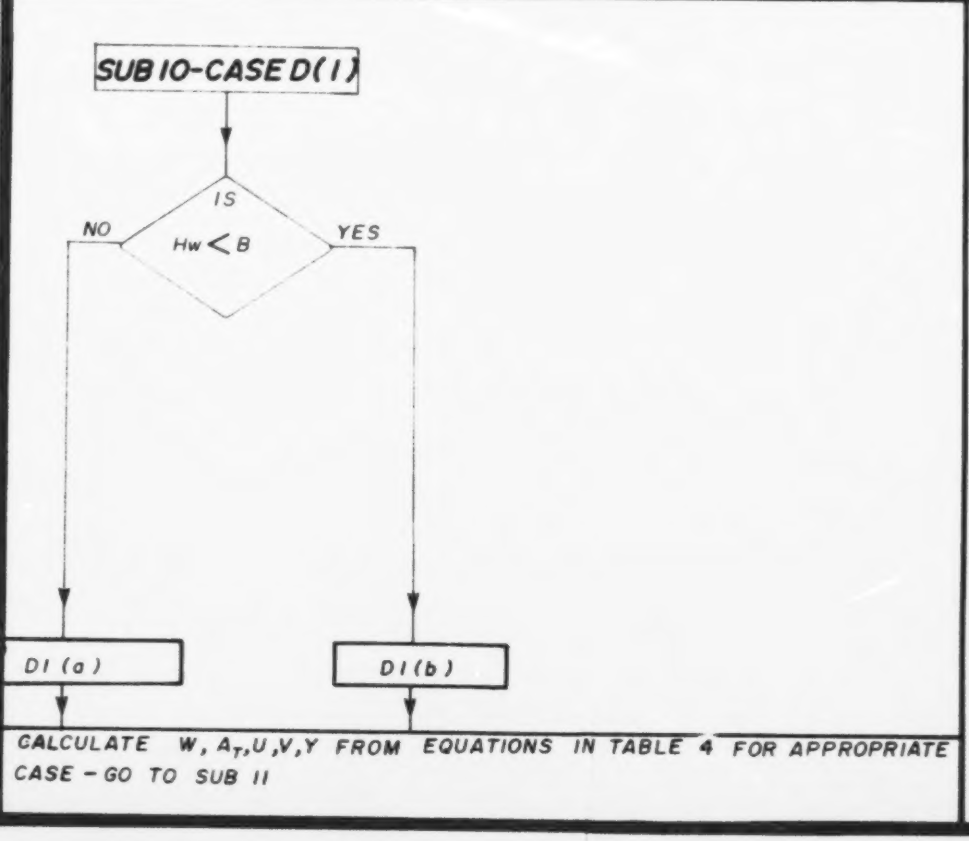

IS $\sum_0^n Kn >$ $H_2 \cot i_2 + x$
NO
YES
IS $\sum_0^n Kn >$ $H_2 \cot i_2 + x + H_1 \cot i_1$
NO
YES
IS $\sum_0^n Kn >$ $(H_1+H_2)\cot\beta$
NO
YES
CASE D
IS $K_{n+1} < (H_1+H_2)\cot\beta - A\cot\beta$
NO
YES
INVALID CASE
IS $K_{n+1} < 0$
NO
YES
ASE
CASE D(1)
GO TO SUB 10
INVALID CASE
Call Is
is Is = 1
NO
YES
PRINT SOLUTION 2 NOT OBTAINED FOR n+1th CRACK
ADD 1 to n
RETURN TO ①
SLOPE ANALYSIS COMPLETE

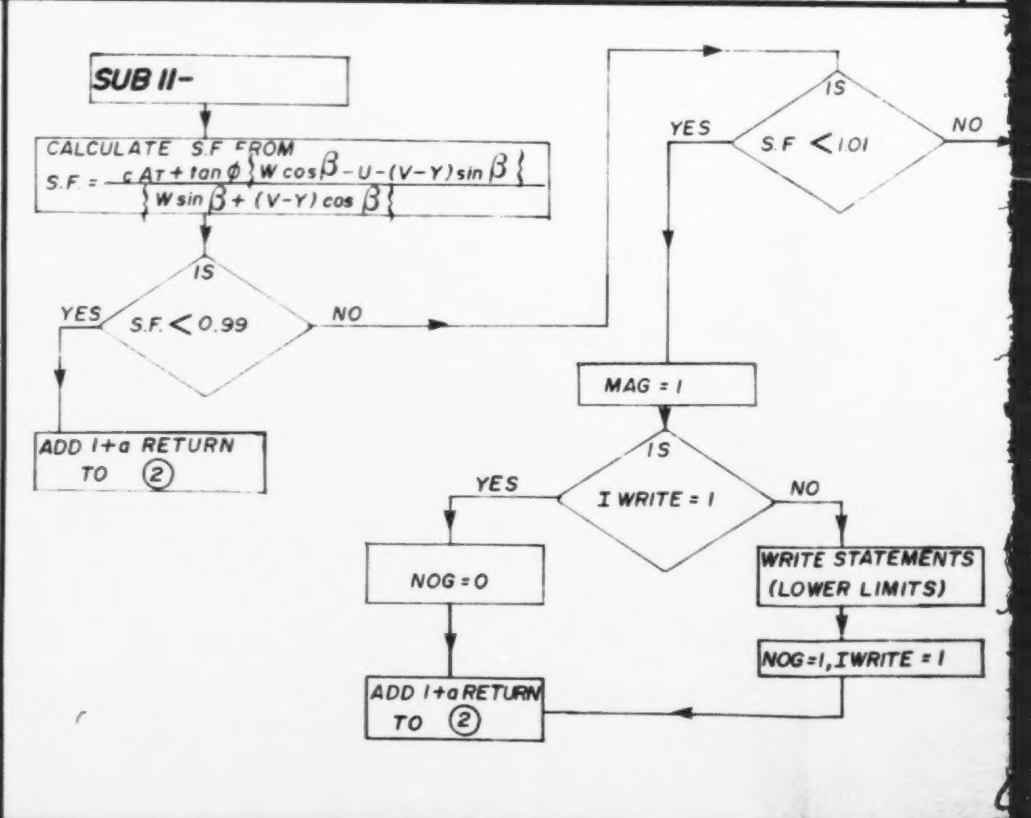

A4(a)
A4(b)
A4(c)
CALCULATE W, A_T, U, V and Y USING EQUATIONS IN TABLE 3 FOR APPROPRIATE CASE — GO TO SUB 11

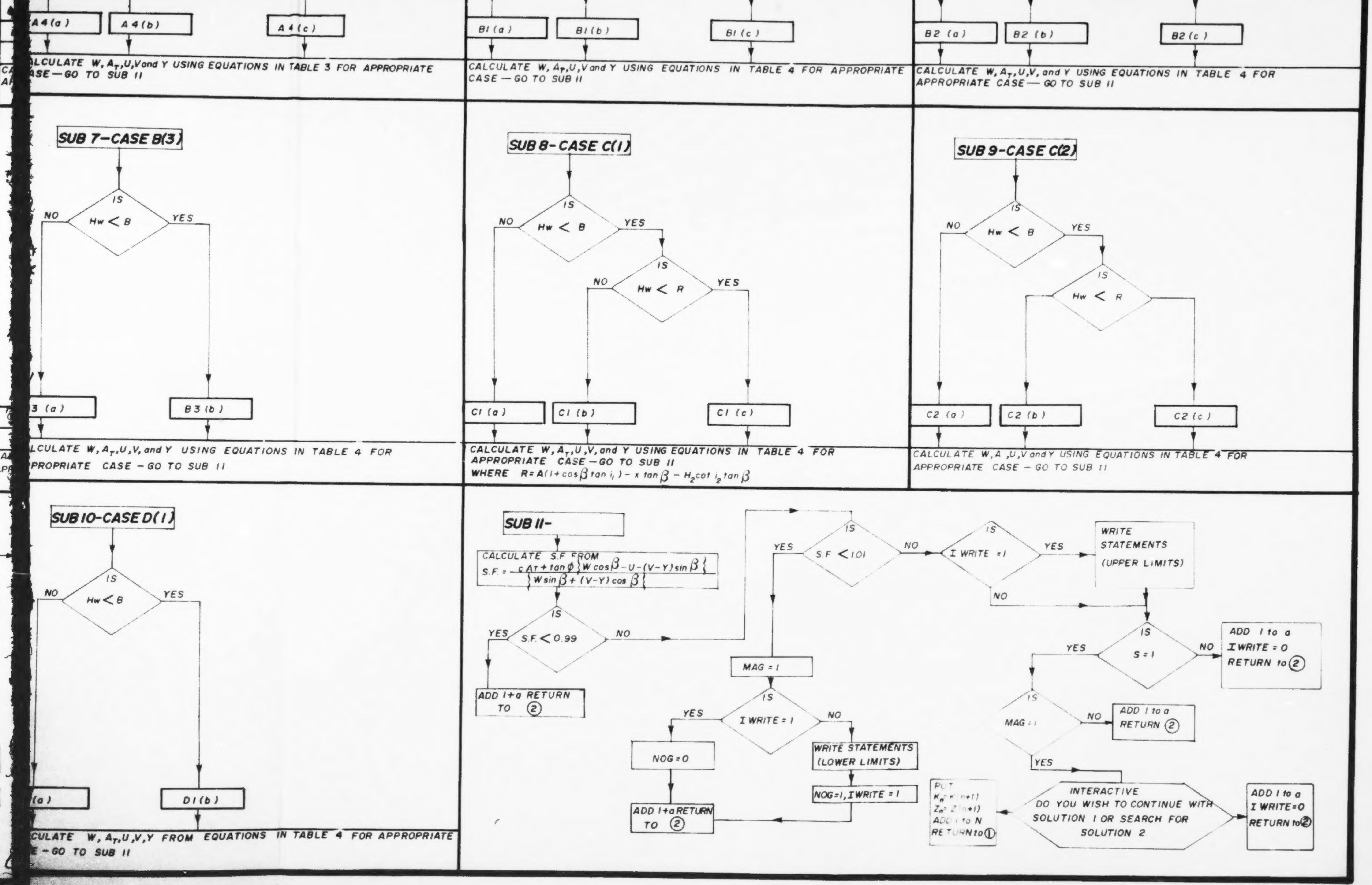

B1(a)
B1(b)
B1(c)
CALCULATE W, A_T, U, V and Y USING EQUATIONS IN TABLE 4 FOR APPROPRIATE CASE — GO TO SUB 11

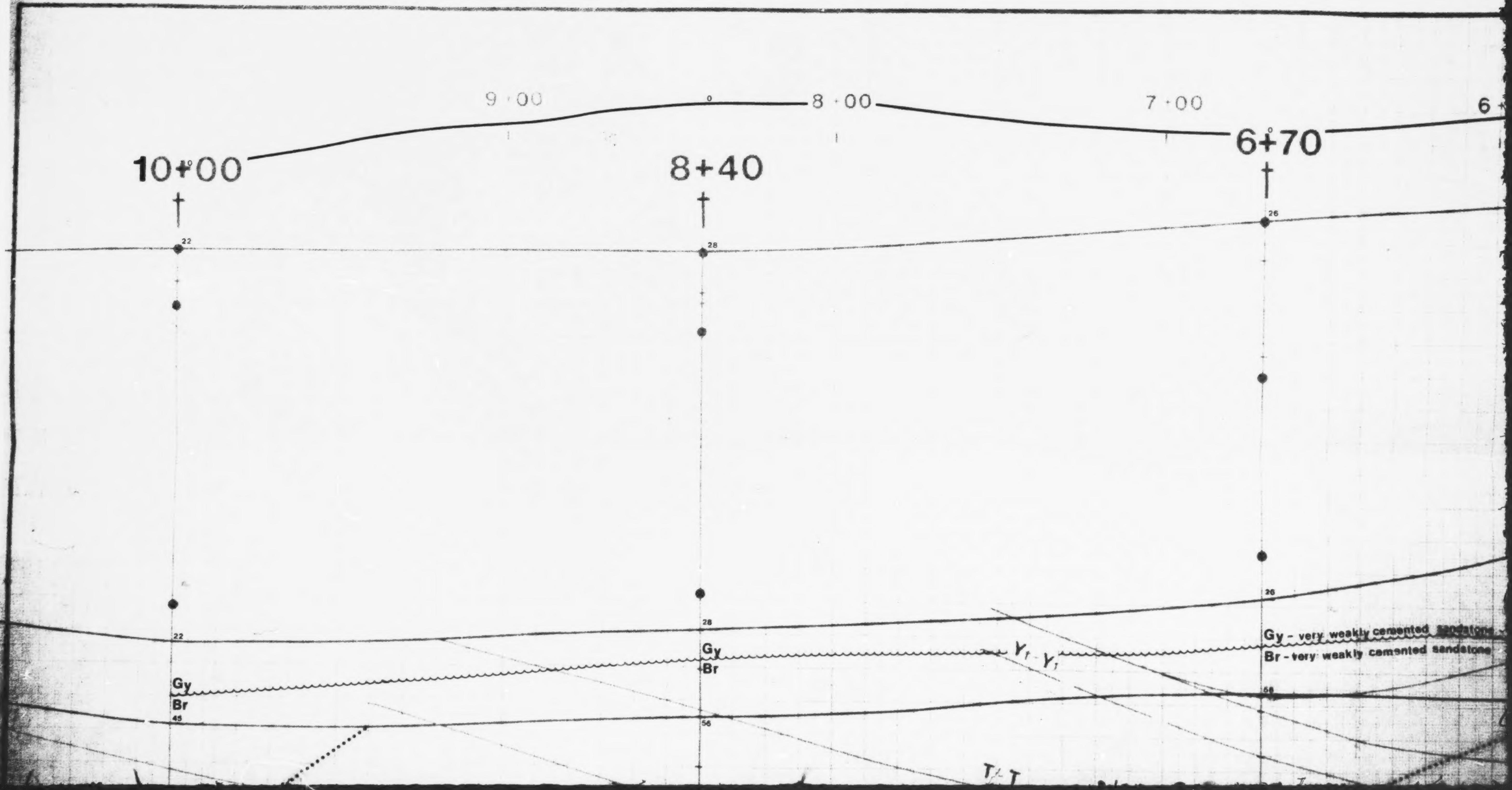

SUB 7–CASE B(3)
IS Hw < B
NO
YES
B3 (a)
B3 (b)
CALCULATE W, A_T, U, V, and Y USING EQUATIONS IN TABLE 4 FOR APPROPRIATE CASE — GO TO SUB 11

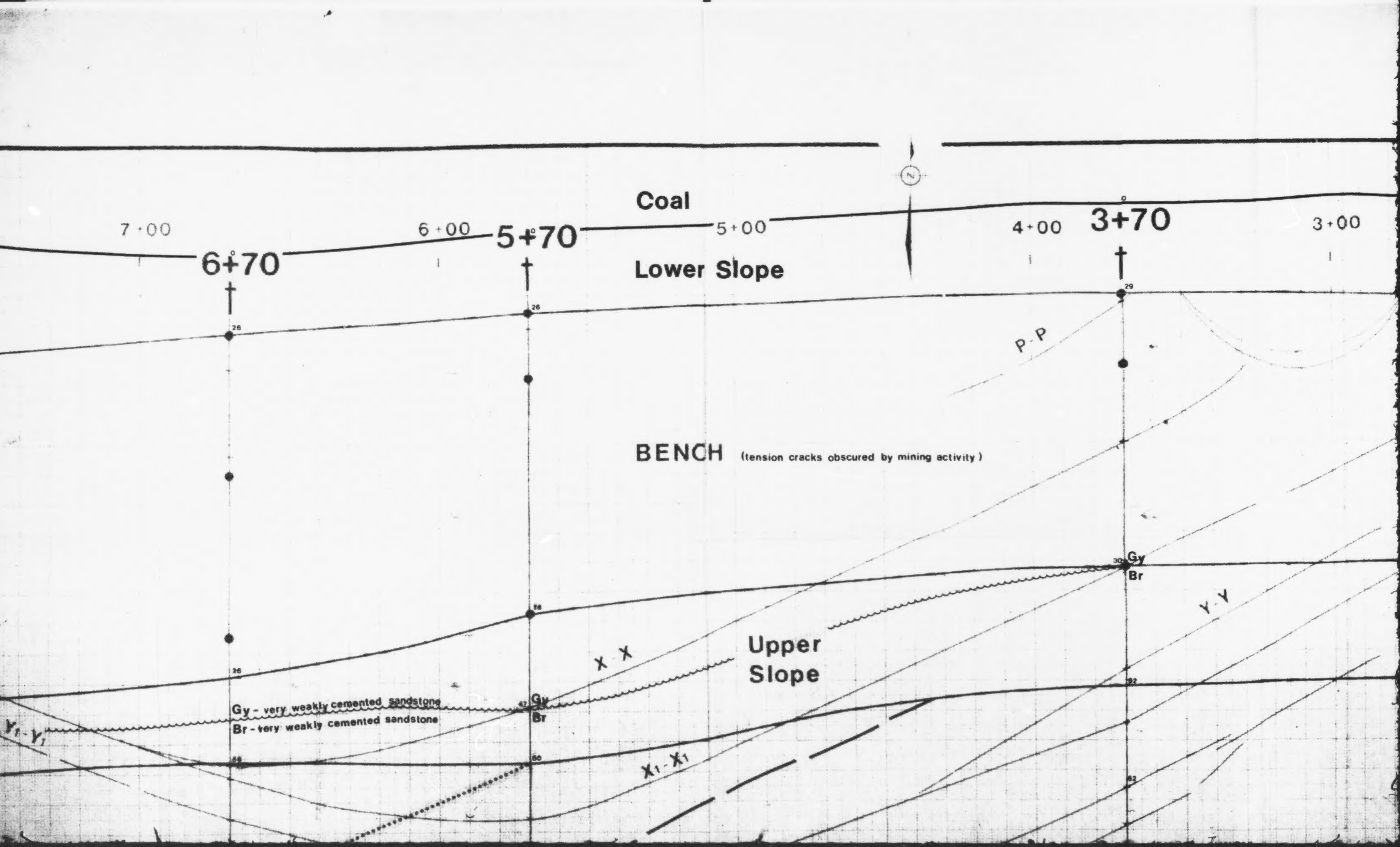

SUB 8–CASE C(1)
IS Hw < B
NO
YES
IS Hw < R
NO
YES
C1 (a)
C1 (b)
C1 (c)
CALCULATE W, A_T, U, V, and Y USING EQUATIONS IN TABLE 4 FOR APPROPRIATE CASE — GO TO SUB 11
WHERE $R = A(1+\cos\beta\tan i_1) - x\tan\beta - H_2\cot i_2\tan\beta$

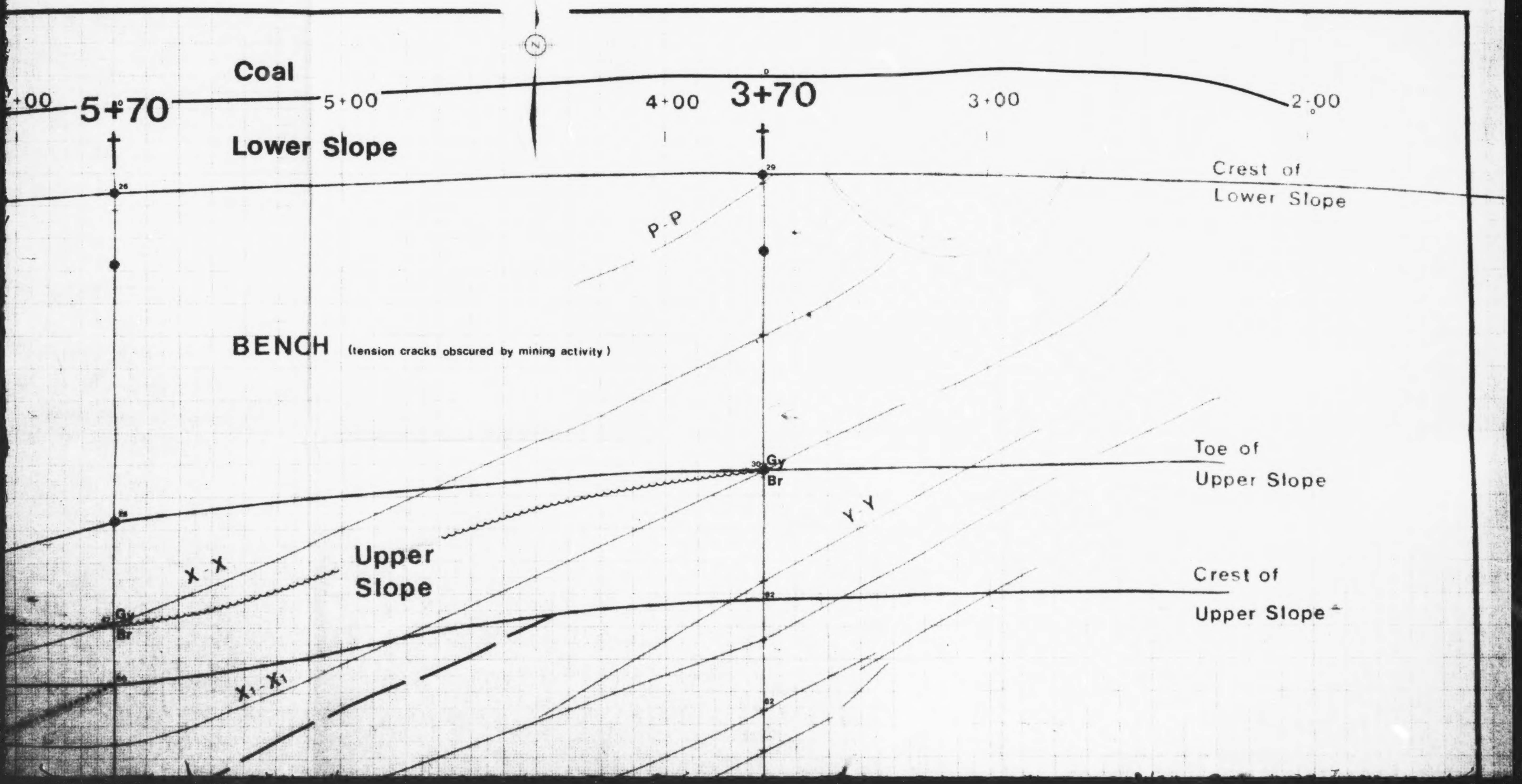

SUB 10–CASE D(1)
IS Hw < B
NO
YES
D1 (a)
D1 (b)
CALCULATE W, A_T, U, V, Y FROM EQUATIONS IN TABLE 4 FOR APPROPRIATE CASE - GO TO SUB 11


SUB 11–
CALCULATE S.F FROM
$S.F. = \frac{cA_T + \tan\phi\{W\cos\beta - U - (V-Y)\sin\beta\}}{\{W\sin\beta + (V-Y)\cos\beta\}}$
IS S.F. < 0.99
YES
NO
ADD 1+a RETURN TO ②
IS S.F < 1.01
YES
NO
MAG = 1
IS I WRITE = 1
YES
NO
NOG = 0
WRITE STATEMENTS (LOWER LIMITS)
NOG=1, IWRITE = 1
ADD 1+a RETURN TO ②

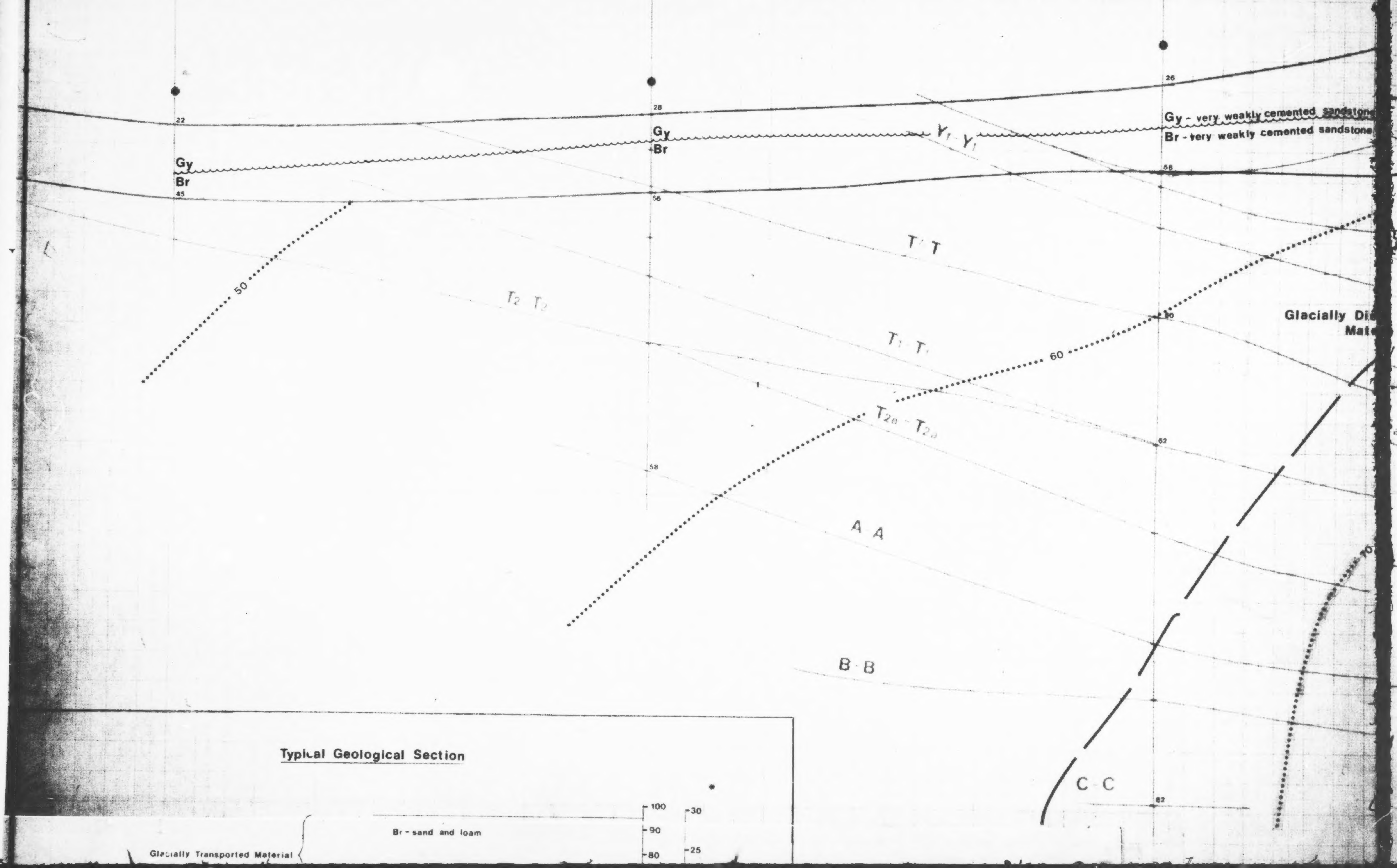

A4(a)
A4(b)
A4(c)
LCULATE W, A_T,U,V and Y USING EQUATIONS IN TABLE 3 FOR APPROPRIATE
ASE — GO TO SUB II
B1(a)
B1(b)
B1(c)
CALCULATE W, A_T,U,V and Y USING EQUATIONS IN TABLE 4 FOR APPROPRIATE CASE — GO TO SUB II
B2(a)
B2(b)
B2(c)
CALCULATE W, A_T,U,V, and Y USING EQUATIONS IN TABLE 4 FOR APPROPRIATE CASE — GO TO SUB II
SUB 7–CASE B(3)
IS Hw < B
NO
YES
3 (a)
B3 (b)
LCULATE W, A_T,U,V, and Y USING EQUATIONS IN TABLE 4 FOR
PROPRIATE CASE – GO TO SUB II
SUB 8-CASE C(1)
IS Hw < B
NO
YES
IS Hw < R
NO
YES
C1 (a)
C1 (b)
C1 (c)
CALCULATE W, A_T,U,V, and Y USING EQUATIONS IN TABLE 4 FOR APPROPRIATE CASE – GO TO SUB II
WHERE $R = A(1+\cos\beta \tan i_1) - x \tan\beta - H_2 \cot i_2 \tan\beta$
SUB 9-CASE C(2)
IS Hw < B
NO
YES
IS Hw < R
C2 (a)
C2 (b)
C2 (c)
CALCULATE W, A ,U,V and Y USING EQUATIONS IN TABLE 4 FOR APPROPRIATE CASE – GO TO SUB II
SUB 10-CASE D(1)
IS Hw < B
NO
YES
(a)
D1 (b)
CULATE W, A_T,U,V,Y FROM EQUATIONS IN TABLE 4 FOR APPROPRIATE
E – GO TO SUB II
SUB II-
CALCULATE S.F FROM
$S.F. = \dfrac{c A_T + \tan\phi \{W\cos\beta - U - (V-Y)\sin\beta\}}{\{W\sin\beta + (V-Y)\cos\beta\}}$
IS S.F. < 0.99
YES
NO
ADD 1+a RETURN TO ②
IS S.F < 1.01
YES
NO
MAG = 1
IS I WRITE = 1
YES
NO
NOG = 0
ADD 1+a RETURN TO ②
WRITE STATEMENTS (LOWER LIMITS)
NOG=1, IWRITE = 1
IS I WRITE = 1
YES
NO
WRITE STATEMENTS (UPPER LIMITS)
IS S = 1
YES
NO
ADD 1 to a I WRITE = 0 RETURN to ②
IS MAG = 1
NO
YES
ADD 1 to a RETURN ②
INTERACTIVE DO YOU WISH TO CONTINUE WITH SOLUTION 1 OR SEARCH FOR SOLUTION 2
PUT $K_R = K(n+1)$ $Z_R = Z(n+1)$ ADD 1 to N RETURN to ①
ADD 1 to a I WRITE=0 RETURN to ②

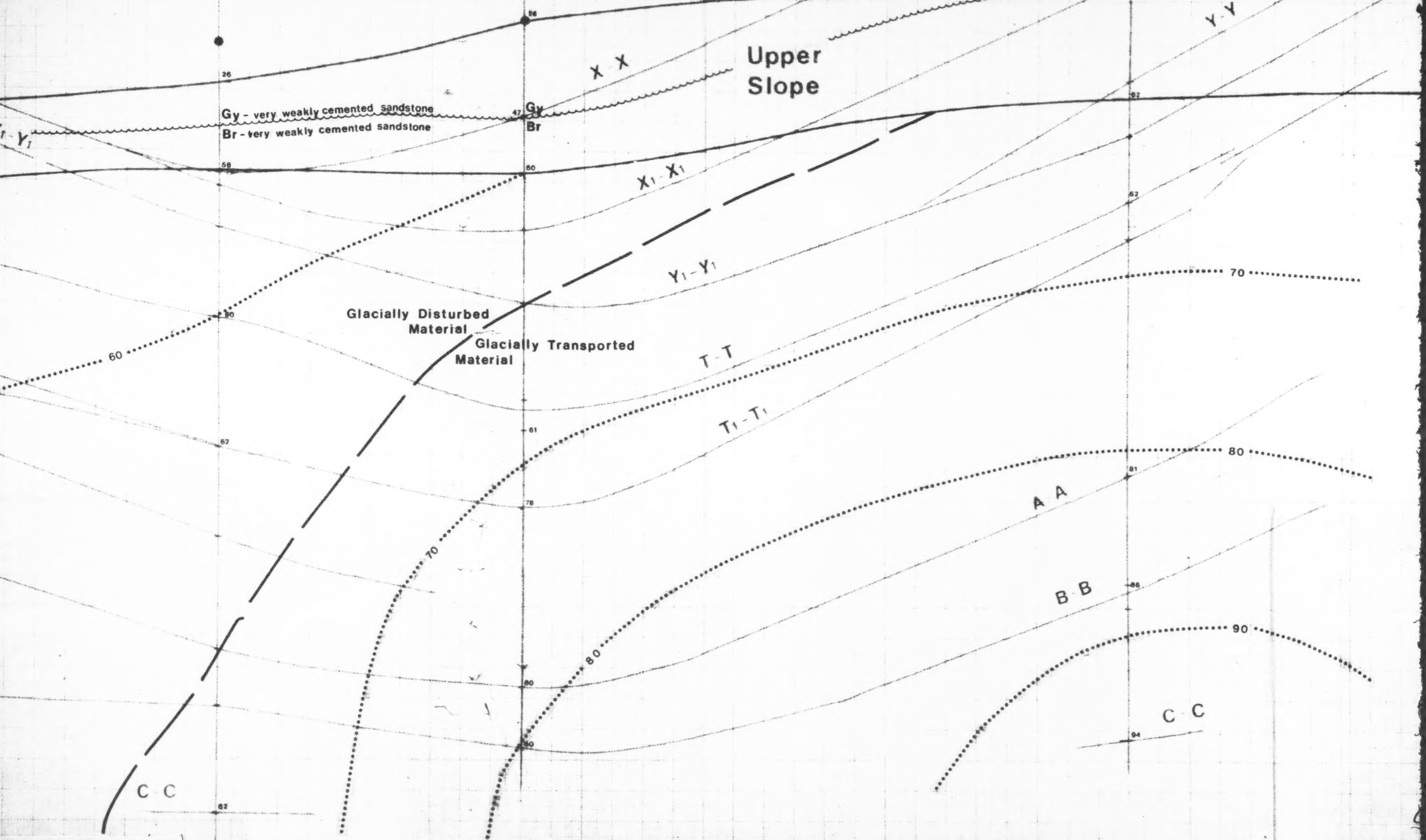

9+00
8+00
7+00
6+
10+00
8+40
6+70
22
28
26
26
22
28
Gy
Br
45
56
58
Gy - very weakly cemented sandstone
Br - very weakly cemented sandstone
Y_1 - Y_1
T - T


Coal
7+00
6+00
5+00
4+00
3+00
6+70
5+70
3+70
Lower Slope
26
26
29
P-P
BENCH (tension cracks obscured by mining activity)
30
Gy
Br
Y-Y
28
X-X
Upper Slope
26
47
Gy
Br
Gy - very weakly cemented sandstone
Br - very weakly cemented sandstone
Y1-Y1
68
60
X1-X1
92
62

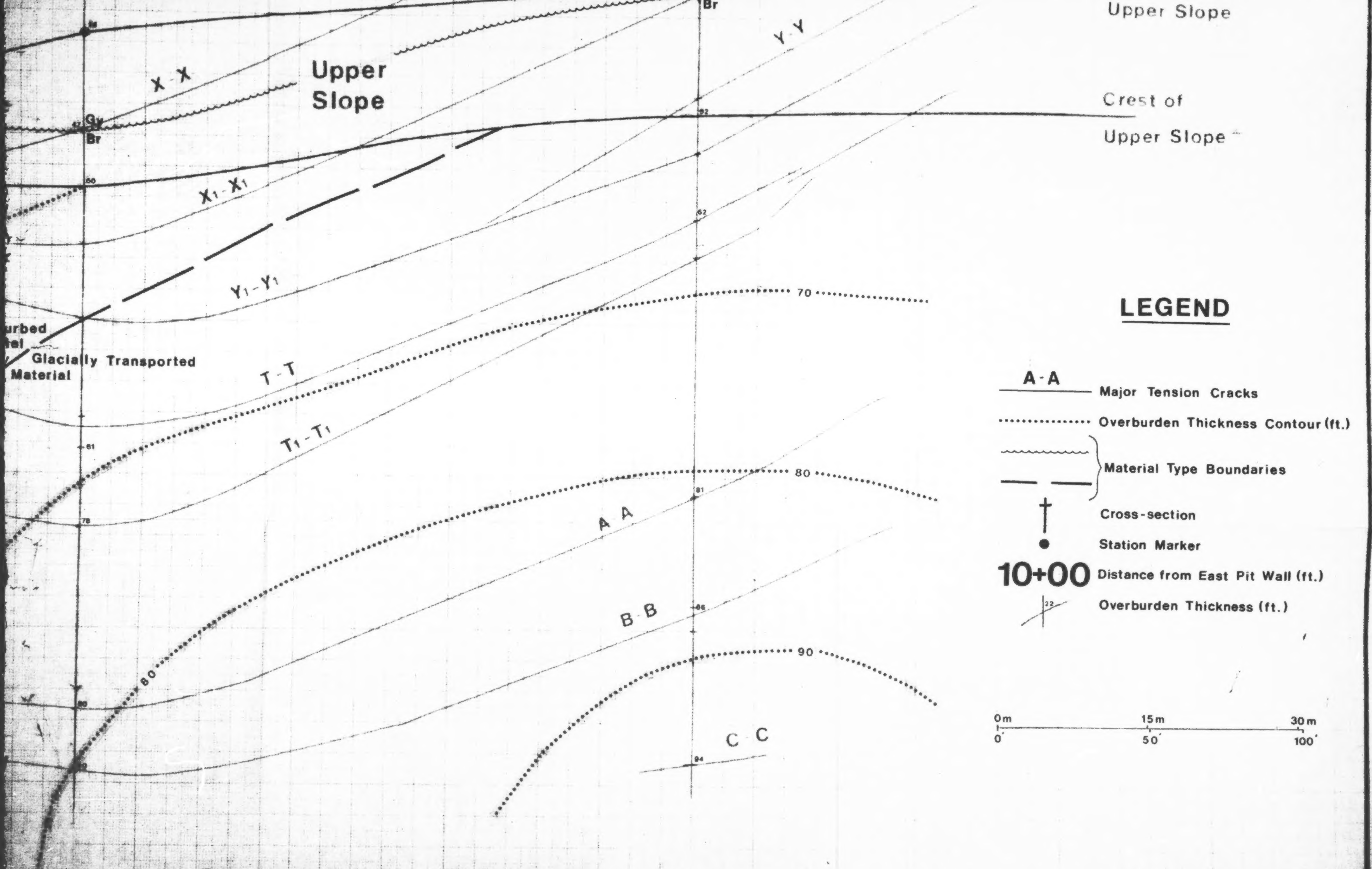


Coal
+00
5+70
5+00
4+00
3+70
3+00
2+00
Lower Slope
26
29
Crest of Lower Slope
P-P
BENCH (tension cracks obscured by mining activity)
30
Gy
Br
Toe of Upper Slope
Y-Y
X-X
Upper Slope
Gy
Br
Crest of Upper Slope
62
X1-X1
62

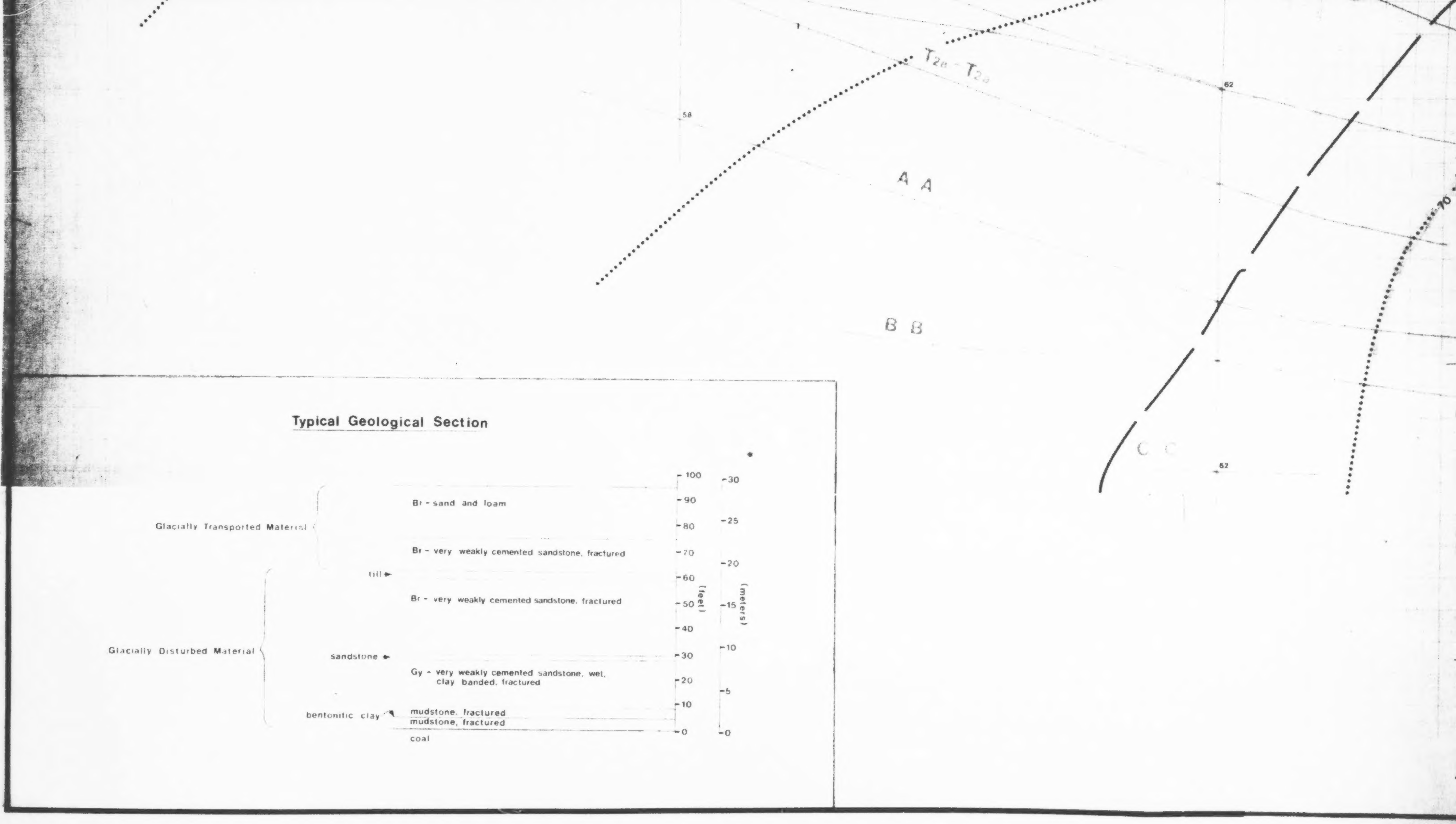

22
28
26
Gy
Br
Gy
Br
Gy - very weakly cemented sandstone
Br - very weakly cemented sandstone
$Y_1 - Y_1$
45
56
58
T' T
50
$T_2 - T_2$
$T_1 - T_1$
60
Glacially Di
Mat
$T_{2a} - T_{2a}$
62
58
A A
B B
70
C C
62
Typical Geological Section
100
90
80
30
25
Br - sand and loam
Glacially Transported Material


Upper Slope
X-X
Y-Y
Gy - very weakly cemented sandstone
Br - very weakly cemented sandstone
Gy
Br
Y1-Y1
X1-X1
Y1-Y1
Glacially Disturbed Material
Glacially Transported Material
T-T
T1-T1
A-A
B-B
C-C
C-C
60
70
70
80
80
90
26
47
58
60
62
61
78
81
86
94
80
82
62

HIGHWALL SLIDE

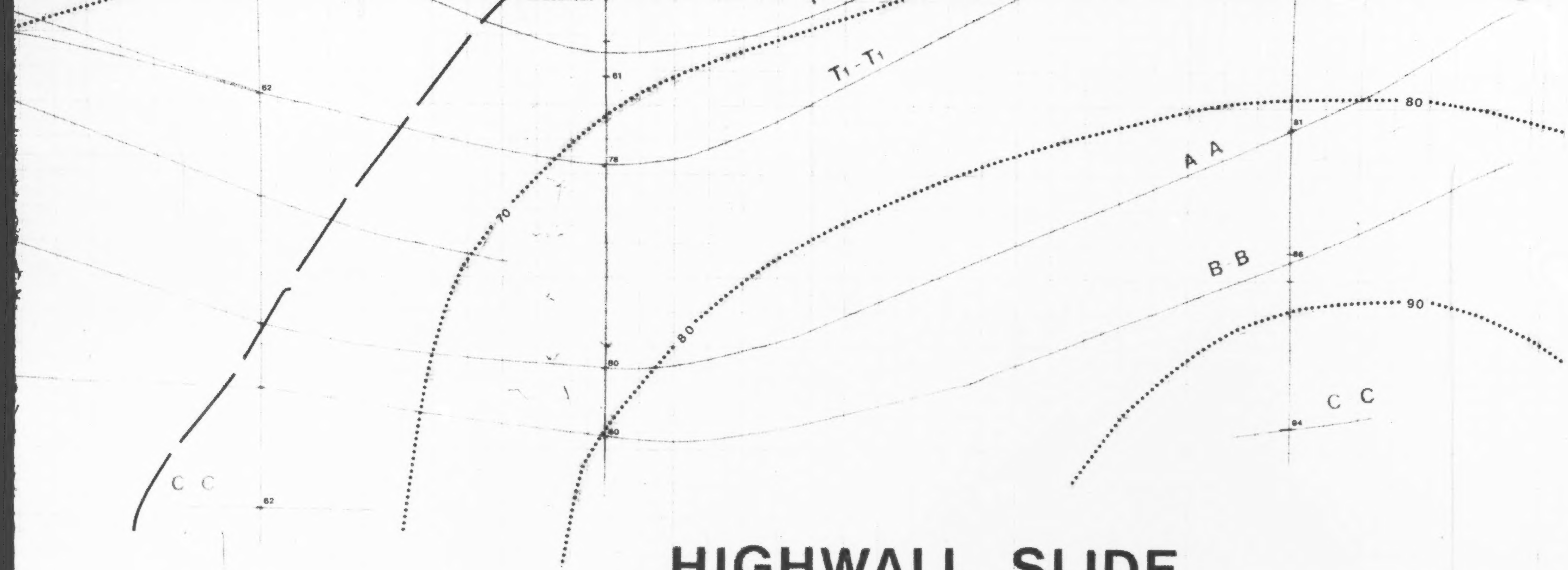

Br
Upper Slope
Y-Y
X-X
Upper Slope
Crest of Upper Slope
Gv
Br
X1-X1
Y1-Y1
urbed
ial
Glacially Transported Material
T-T
T1-T1
70
80
A-A
B-B
90
60
C-C
LEGEND
A-A Major Tension Cracks
Overburden Thickness Contour (ft.)
Material Type Boundaries
Cross-section
Station Marker
10+00 Distance from East Pit Wall (ft.)
22 Overburden Thickness (ft.)
0m 15m 30m
0' 50' 100'

HIGHWALL SLIDE



Typical Geological Section

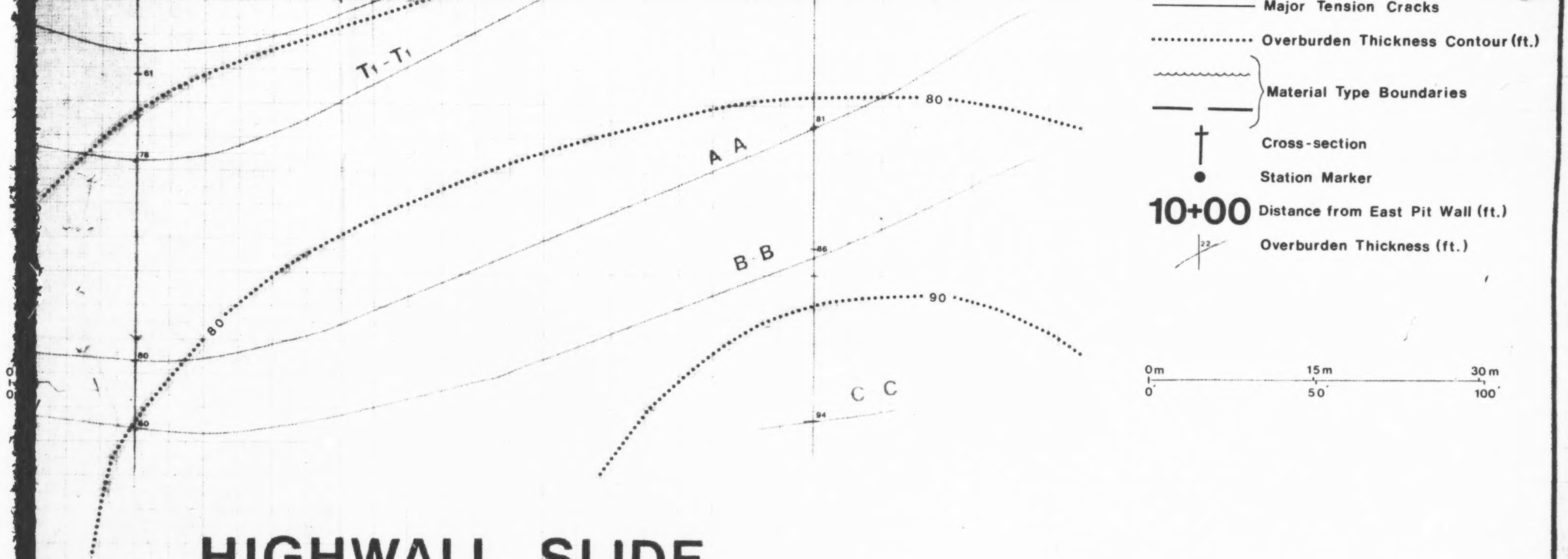
T_{2a} - T_{2a}
58
62
A A
B B
C C
62
70
Glacially Transported Material
Glacially Disturbed Material
Br - sand and loam
Br - very weakly cemented sandstone, fractured
till
Br - very weakly cemented sandstone, fractured
sandstone
Gy - very weakly cemented sandstone, wet, clay banded, fractured
bentonitic clay
mudstone, fractured
mudstone, fractured
coal
100
90
80
70
60
50
40
30
20
10
0
(feet)
30
25
20
15
10
5
0
(meters)


T1 - T1
A A
B B
C C
C C
70
80
80
90
62
61
78
80
80
62
62
81
86
94

HIGHWALL SLIDE
HIGHVALE MINE
PIT 3

April, 1984

DONALD H. GREEN


T₁ - T₁
A A
B B
C C
80
80
90
61
78
81
86
80
60
94
Major Tension Cracks
Overburden Thickness Contour (ft.)
Material Type Boundaries
Cross-section
Station Marker
10+00 Distance from East Pit Wall (ft.)
22
Overburden Thickness (ft.)
0m
15m
30m
0'
50'
100'

HIGHWALL SLIDE
HIGHVALE MINE
PIT 3

April, 1984

DONALD H. GREEN

CMRC